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Submarine landslides around the Canary Islands

Sebastian Krastel,[1,2] Hans-Ulrich Schmincke,[1] Colin L. Jacobs,[3] Roland Rihm,[1] Timothy P. Le Bas,[3] and Bárbara Alibés[4]

Abstract. The morphology and structure of the submarine flanks of the Canary Islands were mapped using the GLORIA long-range side-scan sonar system, bathymetric multibeam systems, and sediment echosounders. Twelve young (<2 Ma) giant landslides have been identified on the submarine flanks of the Canary Islands up to now. Older landslide events are long buried under a thick sediment cover due to high sedimentation rates around the Canary Islands. Most slides were found on the flanks of the youngest and most active islands of La Palma, El Hierro, and Tenerife, but young giant landslides were also identified on the flanks of the older (15-20 Ma) but still active eastern islands. Large-scale mass wasting is an important process during all periods of major magmatic activity. The long-lived volcanic constructive history of the islands of the Canary Archipelago is balanced by a correspondingly long history of destruction, resulting in a higher landslide frequency for the Canary Islands compared to the Hawaiian Islands, where giant landslides only occur late in the period of active shield growth. The lower stability of the flanks of the Canaries is probably due to the much steeper slopes of the islands, a result of the abundance of highly evolved intrusive and extrusive rocks. Another reason for the enhanced slope instability is the abundance of pyroclastic deposits on Canary Islands resulting from frequent explosive eruptions due to the elevated volatile contents in the highly alkalic magmas. Dike-induced rifting is most likely the main trigger mechanism for destabilization of the flanks. Flank collapses are a major geological hazard for the Canary Islands due to the sector collapses themselves as well as triggering of tsunamis. In at least one case, a giant lateral blast occurred when an active magmatic or hydrothermal system became unroofed during flank collapse.

1. Introduction

During the last 10 years, morphological studies of the submarine flanks of ocean islands with swath bathymetry, side-scan sonar and high-resolution seismic systems have demonstrated that giant submarine landslides play an important role during the evolution of volcanic islands. The first systematic morphological study was carried out along the Hawaiian Ridge, revealing at least 68 major landslides more than 20 km long along a 2200-km stretch of the ridge [*Moore et al.*, 1989, 1994]. More recently, submarine giant landslides have been identified or inferred at several other places in the world's oceans, e.g., the Marquesas Islands [*Wolfe et al.*, 1994], La Réunion [*Labazuy*, 1996], Tristan da Cunha [*Holcomb and Searle*, 1991], and the Canary Islands [*Holcomb and Searle*, 1991; *Watts and Masson*, 1995; *Masson*, 1996; *Teide Group*, 1997; *Urgeles et al.*, 1997; 1999; *Funck and Schmincke*, 1998; *Masson et al.*, 1998].

Previous studies at the Canary Archipelago focused largely on single submarine landslide events on the flanks of Tenerife and El Hierro but only briefly considered the general aspect of landsliding around the Canary Islands. Landslides that occurred during the Miocene shield phases [*Funck and Schmincke*, 1998] are long buried under a thick sediment cover due to high sedimentation rates (in general >50 m/Myr) around the Canary Islands [*Schmincke et al.*, 1995; *Schmincke and Segschneider*, 1998]. Prior to this study, nothing had been published about the occurrence of young (<2 Ma) landslides around the older eastern islands.

The ages of volcanoes along the Hawaiian Ridge are mirrored by the ages of their associated landslides, and young landslides are only found at the youngest and most active end of the ridge [*Moore et al.*, 1994]. Individual islands of the Canary Archipelago, in contrast, are characterized by a long volcanic history and multiple phases of volcanism. All islands, except for La Gomera, have been volcanically active during the past 5000 years [*Schmincke*, 1998]. Young giant landslides may therefore occur on the flanks of all islands of the Canary Archipelago.

The aim of this paper is threefold: (1) to describe and characterize previously unknown young giant landslides on the flanks of the Canary Islands, (2) to summarize present knowledge of all major known slides reported from the Canary Archipelago, and (3) to compare these results with those from the well-studied Hawaiian Ridge, thereby contributing to a better understanding of the importance of submarine landslides and the processes of their formation during the evolution of an island group in the Atlantic Ocean.

[1]GEOMAR, Abteilung Vulkanologie und Petrologie, Kiel, Germany.
[2]Now at Fachbereich Geowissenschaften, Universität Bremen, Bremen, Germany
[3]Southampton Oceanography Centre, Southampton, England, UK.
[4]Grup de Recerca Consolidat en Geociències Marines, Dep. Geologia, Dinàmica, Geofísica i P., Universitat de Barcelona, Barcelona, Spain.

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2. Evolution of the Canary Archipelago

The Canary Archipelago, located off the West African continental margin, is one of the largest oceanic island groups in the ocean basins. It consists of seven major islands: Lanzarote and

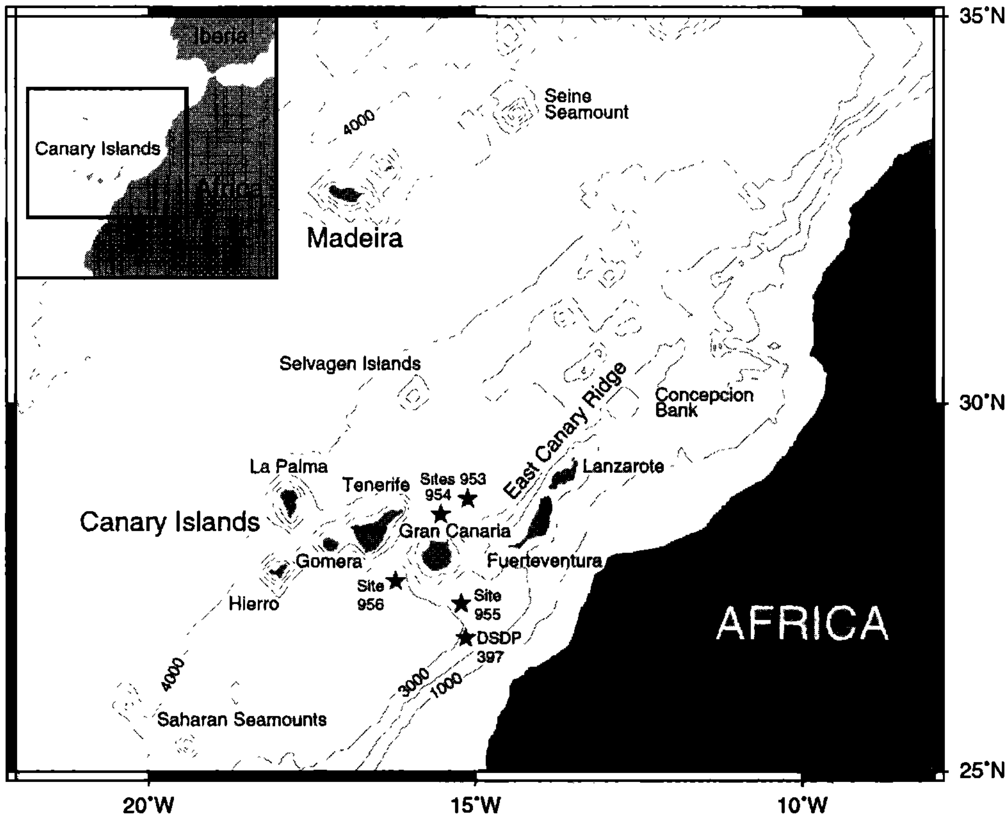

Figure 1. Location map of the Canary Archipelago. DSDP and ODP sites are marked by stars.

Fuerteventura in the east; Gran Canaria, Tenerife, and La Gomera in the center; and El Hierro and La Palma in the west (Figure 1). Lanzarote and Fuerteventura together with Concepcion Bank form the East Canary Ridge, which parallels the African coast, while the central and western islands show an east-west trend and extend into the Canary Basin. The entire archipelago is built on Jurassic oceanic crust [*Banda et al.*, 1981; *Schmincke et al.*, 1998].

The origin of the Canary Islands is still under dispute, and several models have been proposed. A general but slightly diffuse westward age progression of the shield phases of the islands was interpreted as evidence for a hot spot origin of the Canary Islands (Figure 2) [*Wilson*, 1973; *Schmincke*, 1976, 1982, 1998]. However, several features of the Canary Islands differ from the classical hot spot model developed for Hawaii. They include the long volcanic history of individual islands and the entire archipelago, multiple phases of volcanism, ongoing Holocene volcanic activity on all Canary Islands except La Gomera, and the large temporal and spatial variety in the chemical composition of the volcanics [*Schmincke*, 1976; *Hoernle and Schmincke*, 1993]. A connection with tectonic features on the African mainland such as the South Atlas fault or fracture zones in the oceanic lithosphere has been postulated repeatedly [e.g., *Anguita and Hernán*, 1975; *Araña and Ortiz*, 1991]. Seismic data, however, do not show a continuation of the South Atlas fault to the Canary Islands [*Hinz et al.*, 1982; *Stets and Wurster*, 1982], and no fracture zones are presently known to intersect with the Canary Archipelago. A major fault postulated to exist between Tenerife and Gran Canaria [*Bosshard and MacFarlane*, 1970] was not verified [*Funck and Schmincke*, 1998].

The subaerial shields of Gran Canaria, Lanzarote, and Fuerteventura were built in the middle Miocene [*Coello et al.*, 1992; *Bogaard and Schmincke*, 1998]; the shields of La Gomera and Tenerife are middle to late Miocene in age [*Cantagrel et al.*, 1984; *Ancochea et al.*, 1990, 1999]. Shield phases on many islands are followed by a volcanic hiatus up to 5 Myr long (Figure 2). In Fuerteventura, eruptive phases later than the shield-building stage have been identified at 5, 2.9-2.4, 1.8-1.7, 0.8-0.4, and <0.1 Ma, while activity was fairly continuous in Lanzarote from 2.7 Ma to the present [*Coello et al.*, 1992]. Two major volcanic phases following the Miocene shield phase were identified on Gran Canaria, the island with the most complete age data set [*McDougall and Schmincke*, 1976; *Schmincke*, 1976, 1982, 1998, *Schmincke and Sumita*, 1998, *Bogaard and Schmincke*, 1998]. A Pliocene volcanic/magmatic phase produced >100 km^3 of volcanic rocks chiefly between 3.85 and 4.1 Ma (Roque Nublo stratocone). Several cubic kilometers of dominantly mafic basanitic to nephelinitic lavas and large scoria cones were erupted in several episodes between circa 3.2 Ma and 5 ka in the northern part of the island.

The large Cañadas volcano in the center of Tenerife was built on top of the three Miocene, dominantly basaltic shield remnants: Roque del Conde (circa 12 Ma), Teno (circa 5-6 Ma), and Anaga (4-6 Ma) [*Ancochea et al.*, 1990, 1999]. This central volcano is linked to the northeast with the Anaga peninsula by a chain of basaltic emission centers, the Cordillera Dorsal, with peak activity around 0.8 Ma. The Cañadas caldera was filled by the huge double-peak stratovolcano (Pico Viejo and Pico de Teide, 3718 m above sea level (asl)) which has been active to the present [*Ancochea et al.*, 1990]. Postshield volcanism on La Gomera

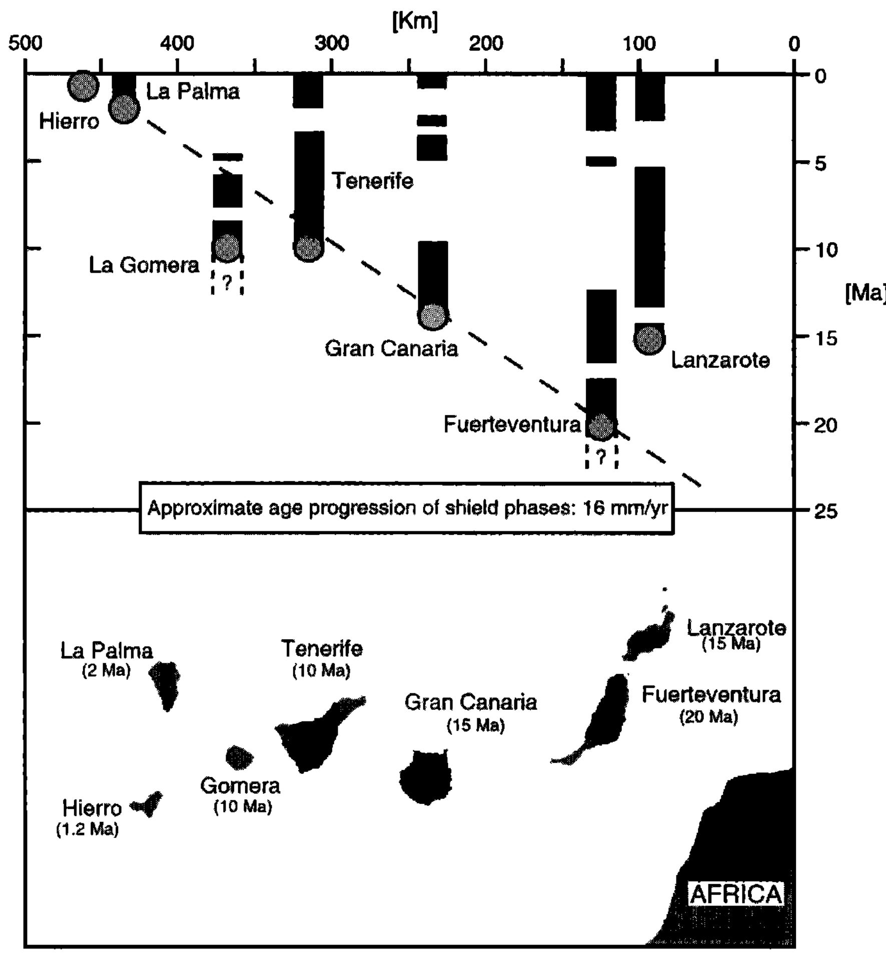

Figure 2. Age distribution of major volcanic phases on the Canary Islands (shield stages shown by circles) [from *Schmincke and Sumita*, 1998]. Volcanic activity of individual islands exceeds 10 Ma and ongoing Holocene volcanic activity occurs on all islands except La Gomera.

occurred between 9 and 3 Ma, but no Quaternary activity is reported from this island [*Cantagrel et al.*, 1984]. La Palma and El Hierro are the westernmost and youngest of the Canary Islands. Subaerial volcanic activity on La Palma started at 2.0 Ma with the building of a large shield volcano. From 0.65 Ma to the present, volcanic activity on La Palma was restricted to the N-S striking ridge continuing southward from the northern shield [*Ancochea et al.*, 1994]. Subaerial activity on El Hierro started around 1.2 Ma [*Guillou et al.*, 1996]. El Hierro has a triangular shape with three well-defined ridges (rifts), a dominant structural feature of many of the Canary Islands [*Carracedo*, 1994]. Ridges are equally prominent in the submarine and major part of the volcanic edifices as demonstrated by the submarine ridges south of La Palma and El Hierro being similar in length to the subaerial ones [*Schmincke et al.*, 2000].

3. Previous Work

Landslides have been considered as a major process to govern the morphology of the Canary Islands for two centuries beginning with *von Humboldt* [1814], who discussed the origin of the broad valley of Orotava on Tenerife. Prior to evidence from seafloor studies, much of the discussion centered around the origin of the large Cañadas depression on Tenerife and the origin of the so-called Caldera de Taburiente on La Palma as well as the large valleys of Tejeda and Tirajana on Gran Canaria [e.g., *Hausen*, 1969, 1971; *Ridley*, 1971; *Navarro and Coello*, 1989]. The recognition of huge debris avalanche deposits on Gran Canaria exceeding 15 km^3 in volume [*Schmincke*, 1987; *García Cacho et al.*, 1994; *Mehl and Schmincke*, 1999] led the way to a more synoptic view in interpreting huge scarps in the island as caused by flank collapse.

On El Hierro, major depressions recognized on land were interpreted as caused by sector collapse. As in the case of Tenerife, much of the evidence was derived from water tunnels (galerias) where the surface of large listric slip planes is commonly covered by a thick altered breccia called Mortalon by the miners (J.M. Navarro, personal communication, 2000]. The origin of the depressions, however, was not finally clarified until *Holcomb and Searle* [1991] found large debris-slide deposits south of El Hierro at the foot of the Julán embayment and interpreted them as derived from the embayment. Another major debris avalanche, El Golfo, was found on the northern flank of El Hierro [*Masson*, 1996; *Urgeles et al.*, 1997].

Watts and Masson [1995] mapped a giant submarine landslide north of Tenerife which extends onshore into the Orotava and Icod valleys. An amalgamation of debris avalanche deposits were identified west of La Palma [*Urgeles et al.*, 1999]. Widespread seismic reflectors were interpreted by *Funck and Schmincke* [1998] as representing debris avalanche/flow deposits resulting from flank collapse especially of Gran Canaria, an interpretation supported by drilling [*Schmincke et al.*, 1995].

The data collected by us document giant landslides offshore the older eastern Canary Islands as well. These new data provide an opportunity to summarize and discuss the present state of knowledge of major subaerial/submarine landslides in the archipelago more fully.

4. Data Collection

The GLORIA long-range side-scan sonar, a Simrad EM12S-120 multibeam echosounder, and a 3.5-kHz echo sounder were used for studying the morphology of the submarine flanks of the Canary Islands and adjacent seamounts in the north and south during Charles Darwin cruise CD109 (October 25 to November 19, 1997). GLORIA is a 6.5-kHz long-range side-scan sonar producing high quality imagery at a range resolution of ~50 m and an along-track resolution of 125-600 m, dependent upon range [*Somers et al.*, 1978]. This reconnaissance mapping system has been refined so that it is now also capable of producing bathymetry by measuring the phase difference of signals arriving at the upper and lower rows of transducers in the GLORIA towfish [*Le Bas et al.*, 1996]. Although the system is still under development, it is possible to measure depth with a vertical resolution of 100 m and a positional accuracy of 250 m.

The Simrad EM12S-120 is a low-frequency 13-kHz multibeam echo sounder with full ocean depth capability. It has an angular coverage of 120° with a swath width of up to 3.5 times ocean depth. Typical accuracies are 0.25% of ocean depth reduced to 1% in areas of steep slopes. Additional bathymetric data were collected during Meteor cruises M24 [*Schmincke and Rihm*, 1994] and M43-1 [*Schmincke et al.*, 2000] using a Hydrosweep multibeam echo sounder. Mercator projected grids with a grid cell dimension of 78 m at 30° N were calculated from the bathymetric multibeam data. The data are displayed using the Generic Mapping Tools (GMT) software [*Wessel and Smith*, 1991].

Sediment echo soundings were collected along all tracks. A 3.5-kHz high-resolution profiling system was used on R/V Charles Darwin. On R/V Meteor, data were recorded with the sediment echographic system Parasound.

Data were collected along more than 100 profiles with a total length of 7700 km around the East Canary Ridge and Gran Canaria as well as south and east of Tenerife, La Gomera, and El Hierro (Figure 3). Some 130,000 km^2 of seafloor were mapped with GLORIA, and some 55,000 km^2 were covered by the EM12 multibeam system. Most tracks were chosen to get complete side-scan coverage. Additional tracks were selected in a few areas to obtain multibeam bathymetric coverage as well. Together with the earlier mapped areas in the region of the western Canaries [*Masson et al.*, 1992], a nearly complete side-scan sonar data set for the Canary Islands is now available.

5. Description of Slides

The landslides described in this paper were identified by a combined analysis of GLORIA sonographs, bathymetric multibeam maps, and 3.5-kHz records. We note that a blocky facies with blocks <50 m doubtlessly exists beyond the slide margins and on the submarine flanks of the islands but was not detected due to the limited resolution of the systems. In addition, some slides were detected based on the analysis of reflection seismic data, drilling, and land-based studies.

The term landslide is used in this paper for all forms of mass movements. *Moore et al.* [1989] divide the large Hawaiian slope failures into two structural types on the basis of the classification of *Varnes* [1978]: slumps and debris avalanches. Slumps are slow rotary movements of largely undeformed masses along discrete shear planes; they have blocky ridges and steep toes. Debris avalanches are, in contrast, fast long-runout mass movements in which fragmentation has reduced the landslide mass to individual blocks during sudden, catastrophic failures; they commonly have a well-defined amphitheater at their head and a hummocky terrain in the lower part. The hummocky terrains of submarine slides resemble those of known rapid catastrophic subaerial volcanic landslides, like those of Mount St. Helens [*Voight et al.*, 1981] and Mount Shasta [*Crandell et al.*, 1984]. Debris avalanches have the potential of triggering large tsunamis [*Moore and Moore*, 1984; *Smith and Shepherd*, 1996].

Submarine slides can become debris flows as the sliding mass progressively disintegrates and continues downslope [*Lee et al.*, 1993], or they can trigger debris flows [*Roberts and Cramp*, 1996]. Debris flows are plastic flows of heterogeneous sediments, commonly including large clasts supported and carried by a matrix of fine sediment [*Lee et al.*, 1993]. The deposits are poorly sorted and with no internal structure.

5.1. El Hierro

5.1.1. Slide 1: El Julán debris avalanche. *Holcomb and Searle* [1991] identified a speckled backscatter pattern characteristic of large debris-slide deposits on a GLORIA sonograph southwest of El Hierro in front of the so-called El Julán embayment (Figure 4 and Table 1). They concluded that the deposits were derived by flank collapse of this part of the island. Former headwall scarps are covered by lavas that postdate the flank collapse. A new GLORIA sonograph shows the speckled pattern typical for a debris avalanche (Figure 5). The hummocky terrain extends as far as 60 km from the island, but the outer edge of the debris avalanche cannot be identified on the sonograph because it is covered by the Saharan debris flow deposits, which are characterized by a high amount of backscatter with downslope-trending lineations on the sonograph (Figure 5). It is identified on a Parasound profile as a 25-m-thick acoustically transparent wedge of sediments onlapping the hummocky surface of the debris avalanche (Figure 6). The Saharan debris flow originated at about 2000 m below sea level (bsl) on the African continental slope south of the Canary Islands [*Embley*, 1982].

At least 1600 km^2 of seafloor are covered by the deposits of the Julán debris avalanche, almost twice the area estimated by *Holcomb and Searle* [1991]. Block size varies considerably in the debris avalanche. Some blocks have diameters up to 2.5 km and are more than 300 m high. Most blocks are much smaller with diameters of 50–500 m (Figure 5) and clearly are derived by collapse, but some of the larger blocks could be volcanic cones.

The Julán embayment represents a volume loss of nearly 100 km^3 according to *Holcomb and Searle* [1991]. They point out that isobaths below 3600 m on the deposits bulge only slightly away from El Hierro. This would indicate that the deposits are generally <50 m thick, whereas reflection seismic data recorded in this area show that the slide deposits have an average thickness of 100 m [*Jacobs*, 1999]. Estimating an average thickness of 50–100 m for the central part of the debris avalanche (i.e., some 75% of the total area) results in volumes of 60–120 km^3,

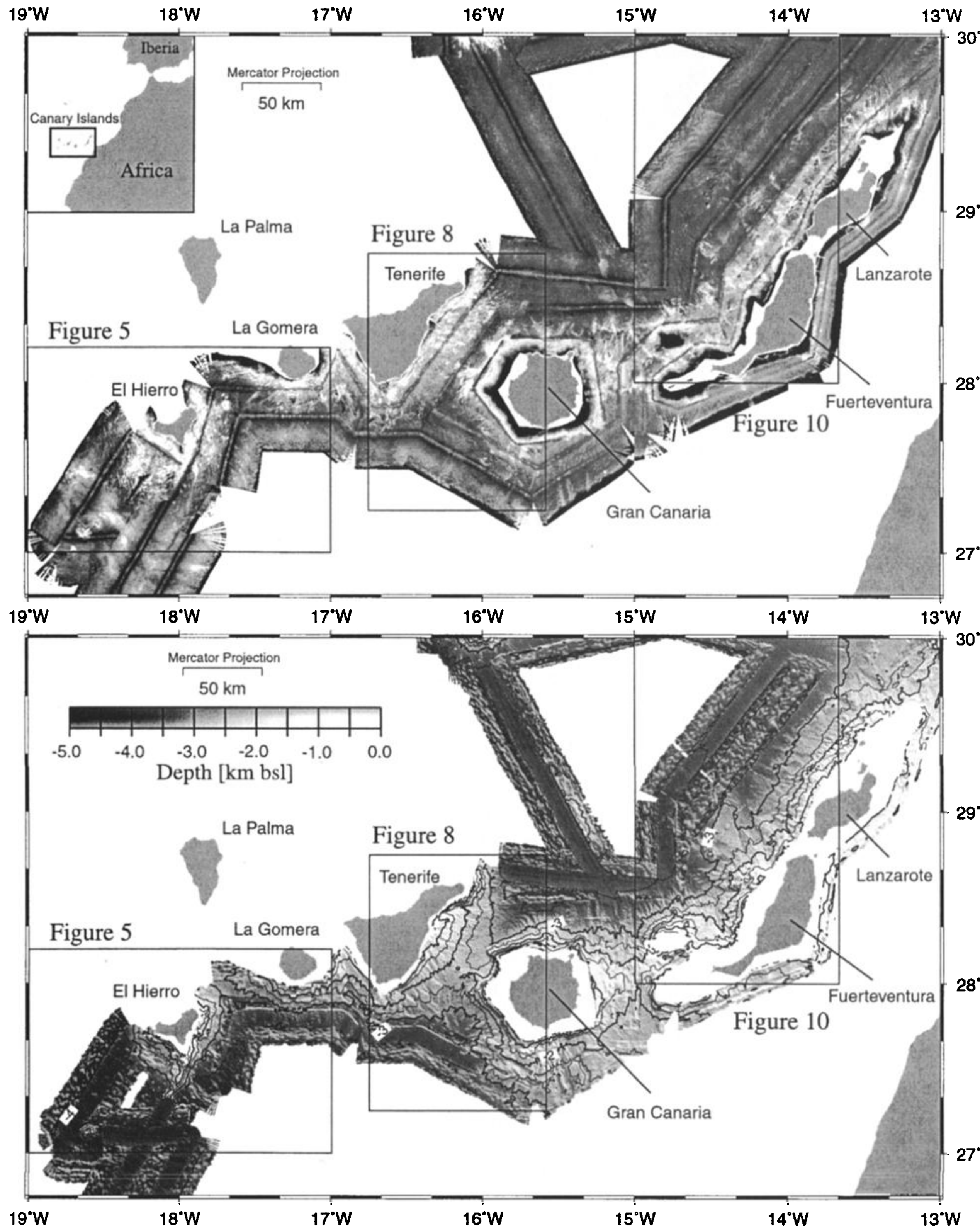

Figure 3. (top) GLORIA mosaic, and (bottom) combined EM12 multibeam and GLORIA swath bathymetry map of Charles Darwin cruise CD109 around the Canary Islands. Dark tones in the GLORIA mosaic are areas of low backscatter. The bathymetric map is shaded by artificial illumination from the north-northeast. The contour interval is 0.5 km, and the 1-km isolines are drawn in bold.

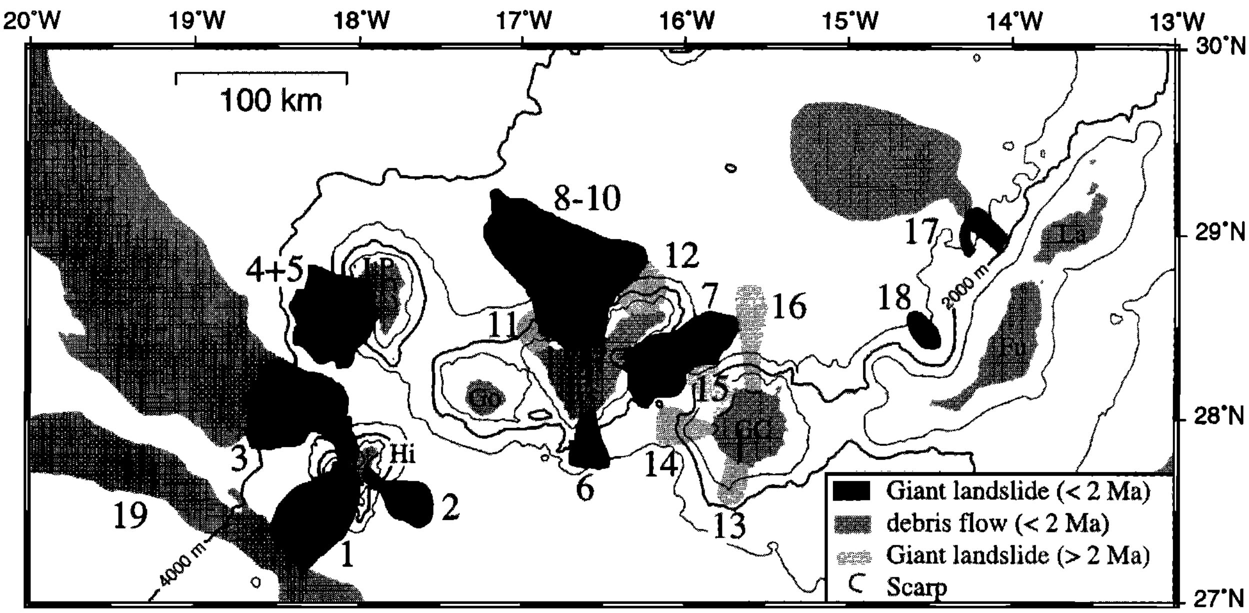

Figure 4. Giant landslides on the flanks of the Canary Islands. (1) El Julán debris avalanche, (2) Las Playas debris avalanche, (3) El Golfo debris avalanche and Canary debris flow, (4) Cumbre Nueva debris avalanche, (5) Playa de la Veta debris avalanche complex, (6) Las Bandas del Sur debris avalanche, (7) Güimar debris avalanche, (8-10) Orotava, Icod, and Roques de García debris avalanches, (11) Teno debris avalanche, (12) Anaga debris avalanche, (13) Roque Nublo debris avalanche, (14) Horgazales basin, (15) Reentrant at the northwest coast of Gran Canaria, (16) Reentrant at the north coast of Gran Canaria, (17) East Canary Ridge landslide, (18) Jandía debris avalanche, and (19) Saharan debris flow. Landslides not covered by the data used in this paper are taken from *Masson et al.* [1993, 1998], *Watts and Masson* [1995], *Masson* [1996], *Teide Group* [1997], *Urgeles et al.* [1997, 1999], *Funck and Schmincke* [1998], and *Cantagrel et al.* [1999]. Volume, ages, and the methods used for identifying the landslides are listed in Table 1.

consistent with the volume loss of the Julán embayment. If the debris avalanche occurred after growth of the basaltic shield stage, it is younger than 190 ka [*Holcomb and Searle*, 1991]. In any case, it must be older than 15 ka, the age of the overlapping Saharan debris flow deposits.

5.1.2. Slide 2: Las Playas debris avalanche. A speckled high backscatter pattern typical for debris avalanche deposits was found off the Las Playas embayment off the southern part of the east coast of El Hierro (Figures 4 and 5 and Table 1). A 3.5-kHz profile parallel to this coast reveals diffractions and blocks typical for a debris avalanche only in the southern part of the profile, while the northern part is characterized by a smooth seafloor (Figure 7).

The deposits of the debris avalanche have a maximum width of 25 km and can be identified up to a distance of 45 km off the coast (Figure 5). An area of ~700 km^2 is covered by the debris avalanche deposits. Single hummocks have diameters of up to 500 m and are at most 100 m high. The 900-m-high scarp at the head of the Las Playas embayment on El Hierro is interpreted as the avalanche headwall. The ~4-km-wide embayment has an amphitheater-like shape and continues ~10 km seaward (Figure 5). The estimated volume of the debris avalanche is 25–35 km^3. Lava flows filling the Las Playas embayment are as old as 145 ka [*Guillou et al.*, 1996], giving the minimum age for the flank collapse.

This debris avalanche can be linked to the San Andres fault system (Figure 5) on El Hierro. The eastern coast is cut by a linked set of east facing faults, ~10 km long and with a prominent main fault scarp a few hundred meters high [*Day et al.*, 1997]. This fault system is interpreted as a gravitational failure which caused the collapse of the southeast part of El Hierro, with subvertical drops in excess of 80-100 m in some places and the formation of the Las Playas embayment [*Carracedo*, 1996]. *Day et al.* [1997] interpret the San Andres fault system as an aborted lateral collapse, in which most of the sliding blocks moved for some hundreds of meters in a coherent fashion and then stopped rather than disaggregating and forming a giant landslide. Disaggregation to a debris avalanche only occurred at the Las Playas embayment. No landslide deposits are visible on the sonograph along the northern part of the east coast, supporting this interpretation.

5.1.3. Slide 3: El Golfo debris avalanche and Canary debris flow. A large debris avalanche, El Golfo, was found on the northern flank of El Hierro (Figures 4 and 5 and Table 1) [*Masson*, 1996; *Urgeles et al.*, 1997]. The 900-m-high onshore scarp that heads the El Golfo embayment is interpreted as the headwall of the debris avalanche. The Canary debris flow evolved downslope from this debris avalanche [*Masson et al.*, 1998]. The relationship between the debris flow and the debris avalanche is unclear. *Masson et al.* [1998] postulate that the debris flow and the debris avalanche occurred simultaneously between 13 and 17 ka, while *Urgeles et al.* [1997] assume that the scarp which constituted the headwall of the Canary debris flow was later covered and/or eroded by the El Golfo debris avalanche. They

Table 1. Summary of Known Submarine Landslides Around the Canary Islands

Number in Figure 4/Name	Area, km^2	Volume, km^3	Age	Methods	References
			El Hierro		
1/El Julán debris avalanche	> 1600	60–120	15–190 ka	land studies bathymetry side-scan sonar sediment echo sounder reflection seismic	*Holcomb and Searle* [1991] *Jacobs* [1999] this paper
2/Las Playas debris avalanche	700	25-35	>145 ka	land studies bathymetry side-scan sonar sediment echo sounder	*Day et al.* [1997] this paper
3/El Golfo debris avalanche	2600	150-180	13–136 ka	land studies bathymetry side-scan sonar reflection seismic sediment echo sounder	*Masson* [1996] *Urgeles et al.* [1997]
3/Canary debris flow	40,000	400	13–17 ka	side-scan sonar bathymetry reflection seismic sediment echo sounder	*Masson* [1996] *Urgeles et al.* [1997] *Masson et al.* [1998]
			La Palma		
4/Cumbre Nueva debris avalanche	780	95	125-536 ka	land studies bathymetry side-scan sonar reflection seismic sediment echo sounder	*Navarro and Coello* [1993] *Ancochea et al.* [1994] *Carracedo et al.* [1999] *Urgeles et al.* [1999]
5/Playa de la Veta debris avalanche complex[a]	1200	650	0.8-1 0 Ma	land studies bathymetry side-scan sonar reflection seismic sediment echo sounder	*Navarro and Coello* [1993] *Ancochea et al.* [1994] *Carracedo et al.* [1999] *Urgeles et al.* [1999]
			Tenerife		
6/Las Bandas del Sur debris avalanche	500	25	<2 Ma	bathymetry side-scan sonar sediment echo sounder	this paper
7/Güimar debris avalanche	1600	>120	<0.83 Ma	land studies bathymetry side-scan sonar sediment echo sounder	*Ancochea et al.* [1990] *Teide Group* [1997] this paper
8/Orotava debris avalanche	5500[b]	1000[b]	0.5–0 8 Ma	land studies bathymetry side-scan sonar sediment echo sounder reflection seismic	*Ancochea et al.* [1990] *Watts and Masson* [1995] *Teide Group* [1997] *Cantagrel et al.* [1999]
9/Icod debris avalanche	5500[b]	1000[b]	130-180 ka	land studies bathymetry side-scan sonar sediment echo sounder reflection seismic	*Ancochea et al.* [1990, 1999] *Watts and Masson* [1995] *Martí et al.* [1997] *Teide Group* [1997] *Cantagrel et al.* [1999]
10/Roques de García debris avalanche	5500[b]	1000[b]	0 6-1.3 Ma	land studies	*Cantagrel et al.* [1999]
Tigaiga debris avalanche	?	?	>2.3 Ma	land studies	*Ibarrola et al.* [1993] *Cantagrel et al* [1999]
11 and 12/Teno and Anaga debris avalanches	?	?	~6 Ma	land studies EM12 backscatter	*Watts and Masson* [1998] *Cantagrel et al.* [1999]

Table 1. (continued)

Number in Figure 4/Name	Area, km²	Volume, km³	Age	Methods	References
			Gran Canaria		
13/Roque Nublo debris avalanche	180 (onshore) 150 (offshore)	14 (onshore) 20 (offshore)	3.5 Ma	land studies reflection seismic ODP Leg 157	*García Cacho et al.* [1994] *Schmincke et al.* [1995] *Funck and Schmincke* [1998] *Mehl and Schmincke* [1999]
Fataga debris avalanches	?	?	9 – 11.5 Ma	land studies ODP Leg 157	*Schmincke* [1998] *Schmincke and Sumita* [1998]
14/Horgazales basin	>1000[c]	>80[d]	14–15 Ma	land studies reflection seismic ODP Leg 157	*Schmincke* [1968] *Funck and Schmincke* [1998] *Schmincke and Segschneider* [1998]
15/Reentrant at the northwest coast of Gran Canaria	>500[c]	>50[e]	14–15 Ma	reflection seismic	*Funck and Schmincke* [1998]
16/Reentrant at the north coast of Gran Canaria	>700	>60	12–15 Ma	reflection seismic ODP Leg 157	*Funck and Schmincke* [1998] *Schmincke and Sumita* [1998]
			East Canary Ridge		
17/East Canary Ridge landslide	Slumps: 400 Debris flow: >2000	Slumps: >35 Debris flow: >20	<100 ka	bathymetry side-scan sonar sediment echo sounder	this paper
18/Jandía debris avalanche	250	25	<2 Ma	bathymetry side-scan sonar sediment echo sounder	this paper

[a] Probably an amalgamation of at least two or three events.
[b] Combined area/volume of Orotava, Icod and Roques de García debris avalanches.
[c] Other parts are covered by the volcanic flank of Tenerife.
[d] Based on an average thickness of 80 m as found in ODP Site 956 [*Schmincke and Segschneider*, 1998].
[e] Based on the volume loss of the reentrant.

postulate an age of between 136 and 21 ka for the debris avalanche on the basis of dating of the youngest rocks affected by the El Golfo scar and the oldest lava postdating the scar.

5.2. La Palma. Slides 4 and 5: Cumbre Nueva debris avalanche and Playa de la Veta debris avalanche complex

The famous and impressive Caldera de Taburiente on La Palma, introduced as the type caldera by *von Buch* [1825], was interpreted as due to erosion by *Lyell* [1853]. More recently, the Arco de Cumbre Nueva and the Caldera de Taburiente have been interpreted as formed by sector collapse [*Navarro and Coello*, 1993; *Ancochea et al.*, 1994; *Carracedo et al.*, 1999].

Bathymetric and backscatter data of the western submarine flank of the island of La Palma reveal a large area of debris avalanche deposits (Figure 4 and Table 1) [*Urgeles et al.*, 1999]. The youngest of the events (536-125 ka), the Cumbre Nueva debris avalanche, extends onshore into the valleys bounded by the Caldera de Taburiente and the Arco de Cumbre Nueva. It covers an area of 780 km² and has an estimated volume of 95 km³. The older Playa de la Veta debris avalanche complex (1.0-0.8 Ma) is probably an amalgamation of at least two or three events rather than the result of a single catastrophic failure. It covers an area of 1200 km² and may represent a total volume of up to 650 km³. *Urgeles et al.* [1999] point out that the ratio of either mean or maximum thickness against area of deposit is some 5 times larger for the La Palma deposits compared to the El Hierro and Tenerife landslides. They conclude that the La Palma landslide masses had a relatively low mobility.

5.3. Tenerife

5.3.1. Slide 6: Las Bandas del Sur debris avalanche.

The area south of Tenerife is morphologically very complex with canyons [*Krastel et al.*, 2000], volcanic cones, and indications of slide material (Figures 4 and 8 and Table 1). An area south of Tenerife extending up to 30 km off the coast and being up to 20 km wide is characterized by the speckled backscatter pattern often associated with a debris avalanche. It is not possible, however, to decide from the sonograph whether this backscatter pattern is caused by a few single blocks or whether these blocks are remnants of a much larger but older, and thus partly buried, landslide. Reflection seismic lines were recorded in this area during Poseidon cruise 236 [*Theilen et al.*, 1997]. No clear seafloor reflections were recorded for large parts of a seismic line across the central part of the deposits, but some parts show a hummocky seafloor morphology [*Jacobs*, 1999]. Another seismic line, ~10 km to the east, crosses the outer margin of the area characterized by the speckled backscatter pattern. The seismic basement is overlain by more than 300 m of sediments, which show internal parallel low-amplitude reflectors [*Jacobs*, 1999]. No large blocks were found on this seismic profile, indicating that the blocks identified on the sonograph in this area are small. The debris avalanche was therefore a small event compared to the flank collapses that led to the formation of the valleys of Güimar and Orotava on Tenerife.

The debris avalanche covers an area of some 500 km². Estimating a maximum thickness of 50 m results in a volume of <25 km³. No headwall of the debris avalanche was identified

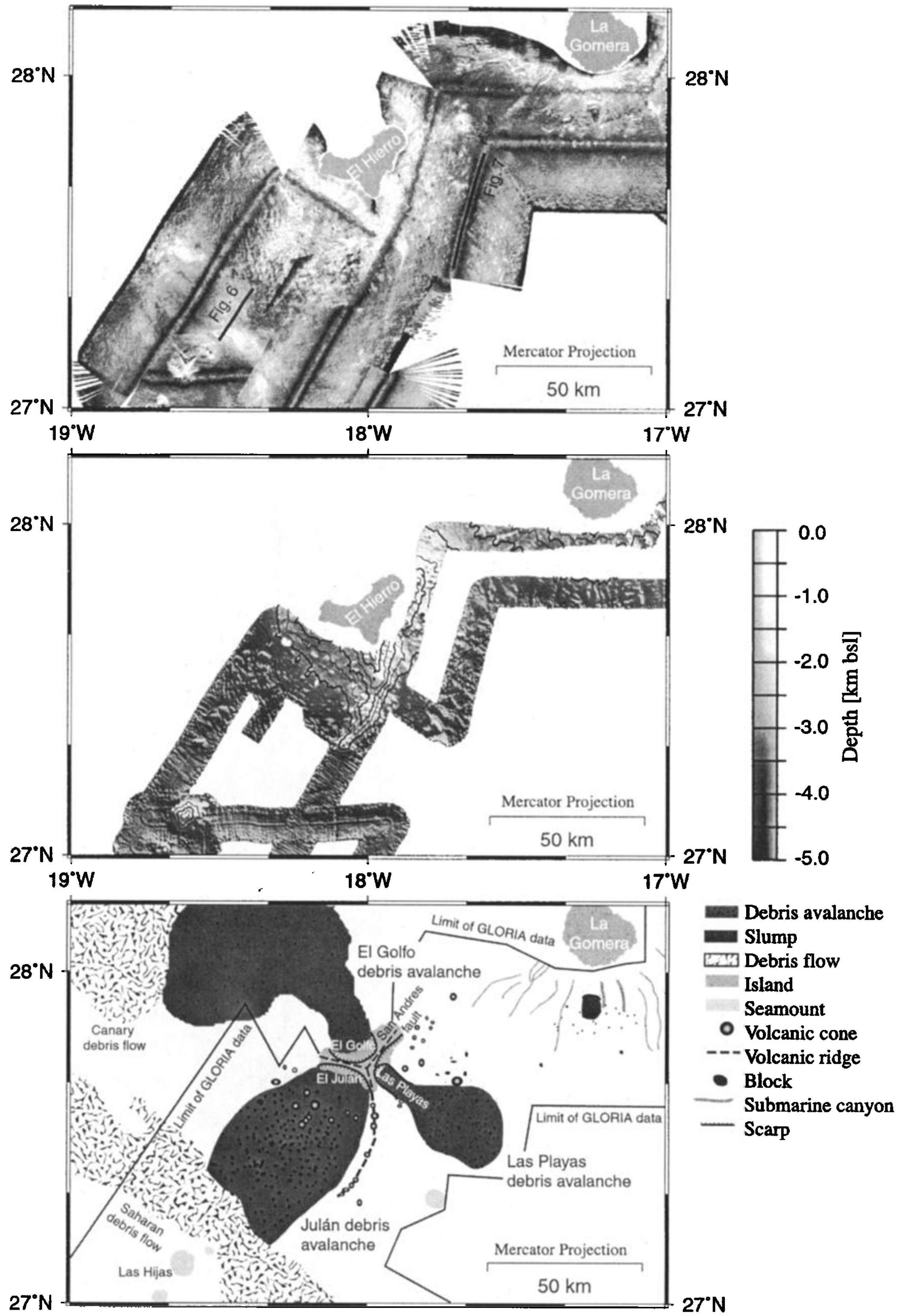

Figure 5. (top) GLORIA mosaic, (middle) bathymetric multibeam, and (bottom) interpretation map around El Hierro. Dark tones in the GLORIA mosaic are areas of low backscatter. The bathymetric map is shaded by artificial illumination from the north-northeast. The contour interval is 0.5 km, and the 1-km isolines are plotted in bold. Features not covered by the data used in this paper are taken from *Masson et al.* [1993, 1998], *Masson* [1996], and *Urgeles et al.* [1997]. See Figure 3 for location.

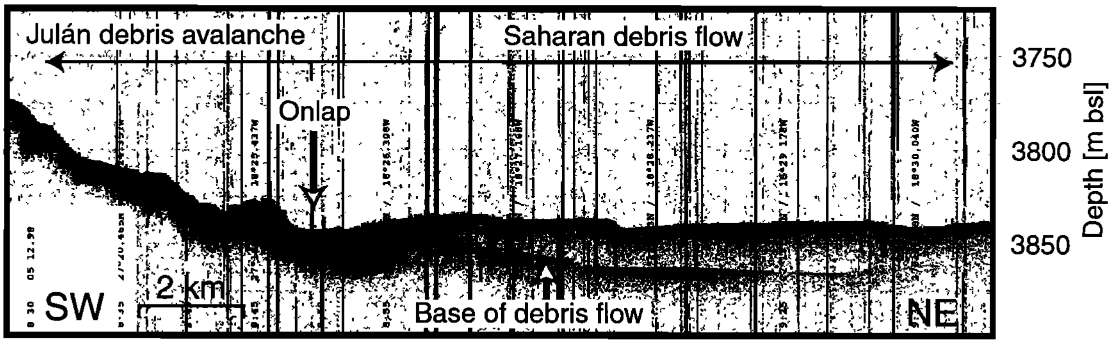

Figure 6. Parasound profile crossing the boundary between El Julán debris avalanche and Saharan debris flow south of El Hierro. The deposits of the 15-ka-old Saharan debris flow onlap the hummocky surface of the El Julán debris avalanche. See Figure 5 for location.

upslope or on Tenerife itself, but a scarp would have probably been filled with volcanic material because of the ongoing voluminous volcanic activity on Tenerife.

The age of the debris avalanche is thought to be younger than 2 Ma because older events would have been buried under sediments due to high sedimentation rates around the Canary Archipelago (see section 6). The debris avalanche is referred to as Las Bandas del Sur debris avalanche, in reference to an area of widespread ignimbrite and lahar fans onshore of the debris avalanche area.

5.3.2. Slide 7: Güimar debris avalanche. A speckled high-backscatter signal caused by a hummocky terrain is found in the northern part of the channel between Tenerife and Gran Canaria (Figure 4 and Table 1). A large number of single blocks of different sizes can be identified on the sonograph (Figure 8). The blocks, located on the submarine flank of Tenerife, must have been deposited by a landslide sourced on Tenerife. Güimar valley is formed by a flank collapse [*Ancochea et al.*, 1990], and hence the hummocky terrain is interpreted as representing the deposit of this landslide, here called Güimar debris avalanche. Single blocks of the debris avalanche are visible up to 70 km off Güimar valley. The deposits cover an area of ~1600 km^2 including the very distal blocks. The central area of the debris avalanche, characterized by a large number of speckles on the sonograph, is only 75% of the total area (~1200 km^2).

A detailed bathymetric map is available for most of the area covered by the Güimar debris avalanche (Figure 8). The relationship between backscatter pattern on the sonograph and bathymetry can be easily seen on Figure 9, where the backscatter pattern is draped on top of the relief. The speckled high-backscatter pattern corresponds to the area with a large number of hummocks on the seafloor.

The largest blocks (most found at distances <10 km to the coast) have diameters of up to 2 km and heights of ~300 m, while the highest number of blocks is found at water depths between 1500 and 3500 m with diameters of up to 1 km and heights of 50-150 m. Only a few isolated blocks were identified in water depths >3500 m and distances >50 km off the coast. Debris flow deposits interpreted to be the distal equivalent of the Güimar debris avalanche are thought to have been detected in Ocean Drilling Program (ODP) drill holes 954 and 953 (Figure 1), the latter 156 km off the coast of Tenerife [*Sumita et al.*, 2000].

The thickness of the avalanche deposits is unknown due to lack of a seismic net in this area. Only a few seismic lines cross the debris avalanche deposits, but deeper reflections are hampered by the large number of hummocks [*Funck*, 1996]. A comparison with other debris avalanches, e.g., the El Golfo debris avalanche west of El Hierro [*Masson*, 1996; *Urgeles et al.*, 1997], debris avalanche deposits west of Réunion Island [*Labazuy*, 1996], and the debris avalanches on the Hawaiian Ridge [*Lipman et al.*,

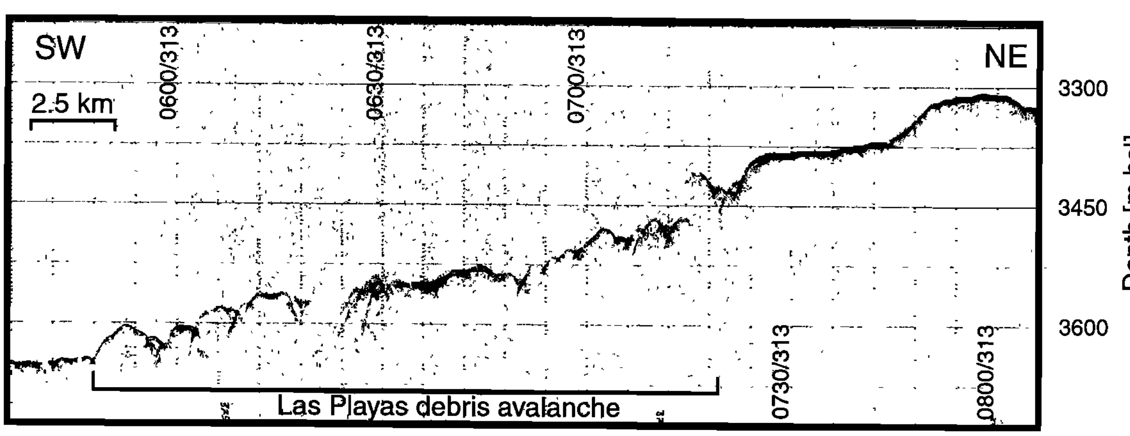

Figure 7. A 3.5-kHz profile across the Las Playas debris avalanche east of El Hierro. The Las Playas debris avalanche is characterized by diffractions and blocks on this profile. See Figure 5 for location.

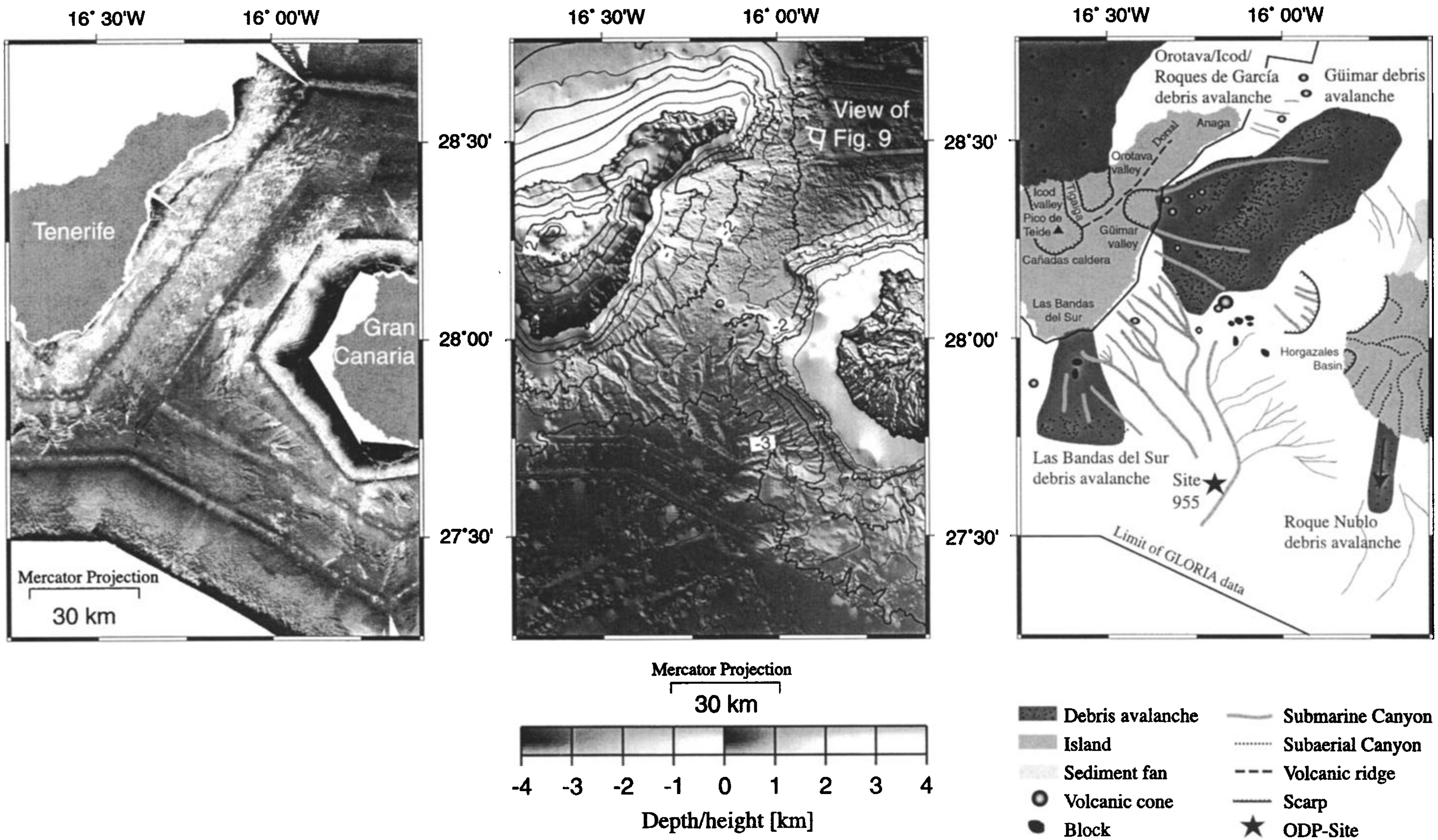

Figure 8. (left) GLORIA mosaic, (middle) bathymetric multibeam, and (right) interpretation map south and east of Tenerife. Dark tones in the GLORIA mosaic are areas of low backscatter. The bathymetric map is shaded by artificial illumination from the north-northeast. The contour interval is 0.5 km, and the 1-km isolines are plotted in bold. Features not covered by the data used in this paper are taken from *Watts and Masson* [1995]. See Figure 3 for location.

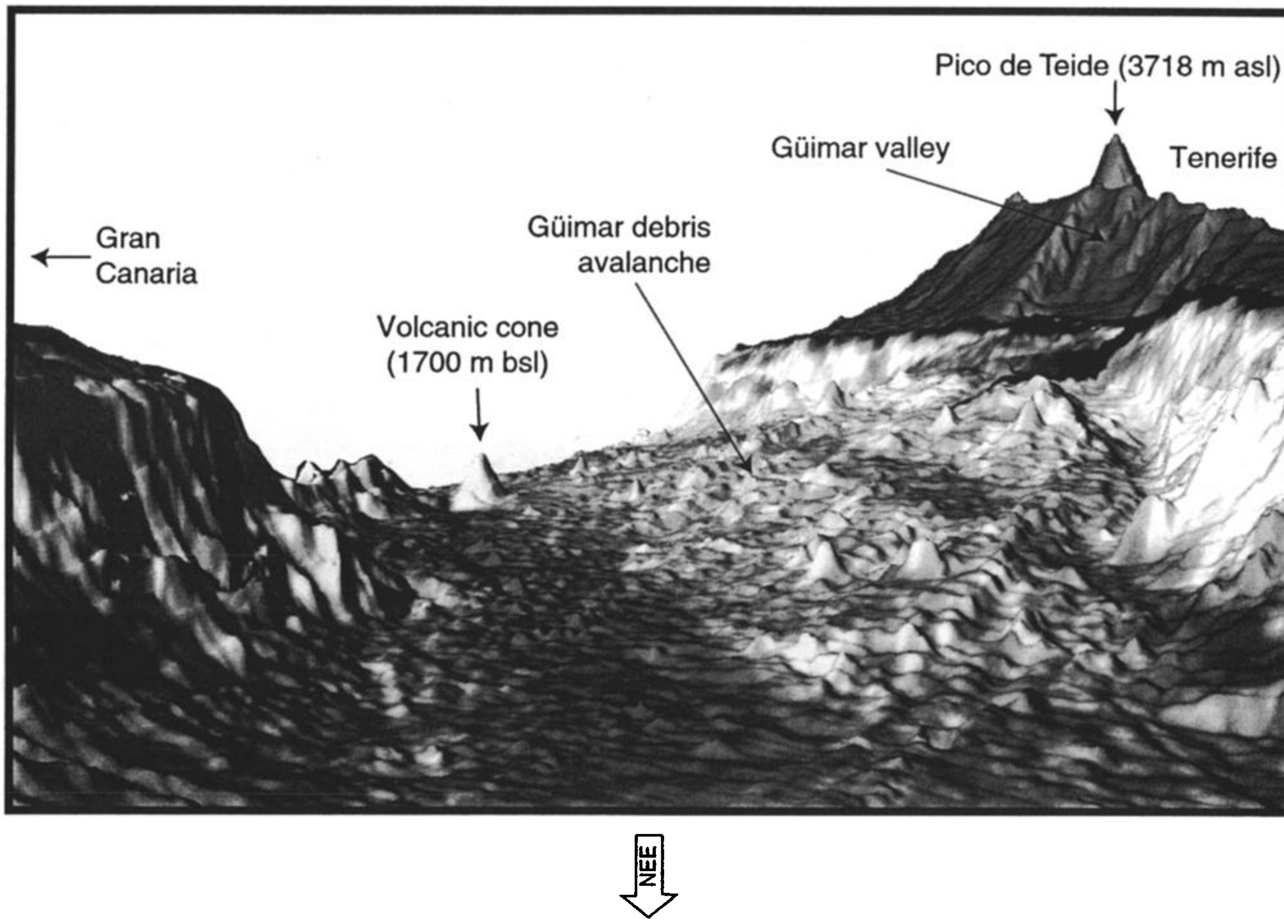

Figure 9. Perspective view of Güimar debris avalanche. Vertical exaggeration is 5. Shading is taken from the GLORIA data. The lighter color of the debris avalanche is due to stronger backscatter of the hummocky terrain. The viewpoint is marked in Figure 8.

1988; *Moore et al.*, 1989, 1994] suggests an average thickness of 100 m for the central part of Güimar debris avalanche, resulting in a total volume of ~120 km^3, probably a minimum value. It is much smaller than the value of >300 km^3 given by the *Teide Group* [1997] for the submarine failure deposits and postfailure volcanic/detritus south of 28°20'N. There, their bathymetric data coverage terminates, thus not taking into account large parts of the debris avalanche. The onshore total volume loss of Güimar valley is only ~50 km^3, significantly lower than the estimated 120 km^3 for the submarine deposits of the debris avalanche. This discrepancy can be explained in two ways. One is an additional contribution from submarine slopes. Alternatively, the debris avalanche deposit may be an amalgamation of more than one collapse event. The deposits associated with the subaerial collapse at Güimar valley are younger than 0.83 Ma, the most recent age obtained for lava flows in the scarp [*Ancochea et al.*, 1990].

5.3.3. Slides 8-12: North directed debris avalanches (Icod, Orotava, Roques de García, Tigaiga, Anaga, and Teno events) and Roque del Conde event. Landslide deposits cover an area of 5500 km^2 north of Tenerife [*Watts and Masson*, 1995; *Teide Group*, 1997]. The landslide is estimated to have a length of 100 km, a width of 80 km, and a volume of ~1000 km^3 (Figure 4 and Table 1) [*Watts and Masson*, 1995]. The debris avalanche deposits extend onshore into the valleys of Orotava and Icod (Figure 8), interpreted to be of landslide origin. The ages estimated for Orotava and Icod debris avalanche are ~500 and ~170 ka, respectively [*Ancochea et al.*, 1990; *Watts and Masson*, 1995].

Geological evidence on Tenerife indicates as much as six north directed debris avalanches. In addition to Icod and Orotava debris avalanches the Tigaiga (>2.3 Ma) and Roques de García (possibly 0.6-0.7 Ma) events affected the Cañadas volcanic edifice, while the old (circa 6 Ma) Anaga and Teno events are related to the corresponding shield volcanoes [*Cantagrel et al.*, 1999]. A major sector collapse has also been involved for the Miocene Roque del Conde shield volcano in southern Tenerife based on a prominent morphological scarp in the shield volcano and a series of distinct debris flow deposits drilled at ODP Site 956 [*Schmincke et al.*, 1995].

5.4. Gran Canaria

No young giant landslides have been reported based on bathymetric data from the submarine volcanic apron around Gran Canaria, but there is strong evidence for the occurrence of giant landslides during the Miocene and Pliocene based on seismic data, drilling, and land-based studies.

5.4.1. Slide 13: Roque Nublo debris avalanche. The ~3.5 Ma Roque Nublo debris avalanche (Figures 4 and 8 and Table 1) is well exposed onshore and resulted from the collapse of the Pliocene Roque Nublo stratocone on Gran Canaria. Its estimated subaerial volume is at least 14 km^3 [*García Cacho et al.*, 1994; *Mehl and Schmincke*, 1999]. A submarine fan offshore southern Gran Canaria is interpreted as a continuation of this avalanche deposit whose coastal exposures in southern, northeastern, and northwestern Gran Canaria clearly show that the debris avalanches entered the ocean all around the island. The submarine volume of the avalanche deposits south of Gran Canaria is at least 20 km^3 based on reflection seismic data [*Funck and Schmincke*, 1998].

5.4.2. Slides 14–16: Reentrants at the northwest and northern coast of Gran Canaria and Horgazales basin. At least three buried Miocene landslides around Gran Canaria (Figure 4 and Table 1) were identified on the basis of the analysis of reflection seismic, borehole data, and land studies. Two reentrants at the northwest and north coast of Gran Canaria (GC) are interpreted to have been formed by major sector collapses at the end of the shield-building stage [*Funck and Schmincke*, 1998; *Schmincke and Sumita*, 1998]. Another scarp in the 14–15 Ma shield volcano of Gran Canaria, named Horgazales basin (Figure 4 and Table 1), was rapidly filled with younger shield basalts [*Schmincke*, 1968]. A huge debris flow deposit drilled 45 km southwest of GC at ODP Site 956 is interpreted to have been derived from this collapse. Unusual bedded deposits overlying this >80-m-thick massive deposit were interpreted as tsunamis deposits that resulted from the collapse of the island flank [*Schmincke and Segschneider*, 1998]. Land studies and borehole data provide strong evidence for at least three additional flank collapses during the deposition of the Fataga Formation between 11 and 9.5 Ma [*Schmincke*, 1998; *Schmincke and Sumita*, 1998].

5.5. Eastern Canaries

5.5.1. Slide 17: East Canary Ridge landslide. The deposits of a submarine mass-wasting event offshore the gap between the islands of Lanzarote and Fuerteventura, referred to as East Canary Ridge landslide, consist of three parts: (1) a rotational slump, (2) a sediment slump, and (3) a debris flow (Figures 4 and 10 and Table 1).

An area almost 25 km long and 15 km wide at a water depth of 2800-3300 m is characterized by its overall coherent lobate shape with a series of contour-parallel targets of high acoustic backscatter on the sonograph (Figure 10). A 3.5-kHz profile across parts of this feature shows the characteristic step pattern of a series of rotational slip planes, each varying up to 100 m in height (Figure 11), interpreted as a rotational slump. Two large valleys are located farther upslope, the potential source area for the rotational slump, but no clear-cut scarp can be identified. An area just south of the rotational slump is characterized by a general high level of acoustic backscatter on the sonograph, typical for a sediment slump (Figure 10). A 6-km-wide and more than 200-m-deep submarine canyon with steep walls on either side occurs immediately upslope of this slide. An area of high acoustic backscatter with small arcuate shadows to either side at a depth of 3000 m bsl is interpreted as the main failure surface of this sediment slump. The sediment slump joins with the rotational slump at the base of the slope.

An up to 65-km-wide and more than 70-km-long area farther downslope from these slope failures is characterized by a generally high amount of backscatter with a lineated downslope-trending fabric marked by linear bands of contrasting backscatter (Figure 10). The backscatter pattern is typical for sedimentary debris flow deposits [*Kidd et al.*, 1985]. *Masson et al.* [1993, 1998] interpret similar features of the Canary and Saharan debris flows as being due to streams of debris of different character and texture. The total length of this area cannot be determined because of incomplete GLORIA coverage. This type of backscatter pattern is not visible, however, on a profile between the Canary Islands and the Selvagen Islands (Figure 3), giving a maximum length of 120 km. A 3.5-kHz profile varies significantly across the debris flow deposits (Figure 12). The northern boundary is characterized by a change from a distinct to a prolonged echo, typical for areas where a debris flow deposit is too thin to be resolved by the echosounder [*Masson et al.*, 1992]. The debris flow deposits onlap the sediments at the southern boundary, suggesting that they are thicker than at the northern boundary. The northern part of the debris flow deposit shows some subbottom penetration without an internal relief. Almost no subbottom penetration is visible in the central part, but several small ridges up to 10 m high and 2 km long can be identified. The southern part is dominated by a very diffuse bottom echo. The debris flow deposits are therefore interpreted as an amalgamation of several events with different echo characters.

The volume of the East Canary Ridge landslide is difficult to estimate because detailed information of its thickness is lacking. The rotational slump covers an area of some 300 km^2. It has a steep, 100-m-high toe, the minimum thickness of this feature, resulting in a minimum volume of 30 km^3. The debris flow deposits cover at least 2000 km^2 of seafloor, but GLORIA coverage of the distal part of the debris flow deposits is not available. The base of the debris flow deposits could only be identified along a small part of a 3.5-kHz profile across the southern margin (Figure 12). The debris flow deposits are ~15 m thick at this point, while they are thinner at its northern margin. The prolonged echo of the 3.5-kHz profile is typical for deposits thinner than 5 m, which cannot be resolved by the system. Using 10 m as an average thickness for the debris flow deposits results in a volume of 20 km^3. The sediment slump covers an area of ~90 km^2, its volume is probably <5 km^3.

No sediment cover of the debris flow deposits can be detected on the 3.5-kHz profile, indicating that it is young (<100 ka). The debris flows and the rotational slump are thought to represent simultaneous events (see section 6).

5.5.2. Slide 18: Jandía debris avalanche. A speckled backscatter pattern ~35 km northwest of the Jandía peninsula, southern Fuerteventura, is caused by the deposits of a debris avalanche, here called Jandía debris avalanche (Figures 4 and 10 and Table 1). The debris avalanche deposits cover an area of 25 x 10 km. The area upslope of the debris avalanche deposits is characterized by a variety of canyons and gullies. Large canyons are found on both sides of the debris avalanche area as well. The source area of the debris avalanche remains unclear. No major submarine or subaerial scarps are located upslope of the deposits, but a submarine origin is favored because of the limited size of the debris avalanche area and the large distance (35 km) to the coast of Fuerteventura. The estimated volume of the deposits is 25 km^3. The deposits must be relatively young (<2 Ma) because they are still visible on the sonograph despite the high sedimentation rates in this area (see section 6).

6. Discussion

Most known submarine landslides have been inferred from detailed morphological studies of the seafloor by side-scan sonars and bathymetric multibeam systems. The spatial correlation of a large block field with a major scarp on the flanks of an island has

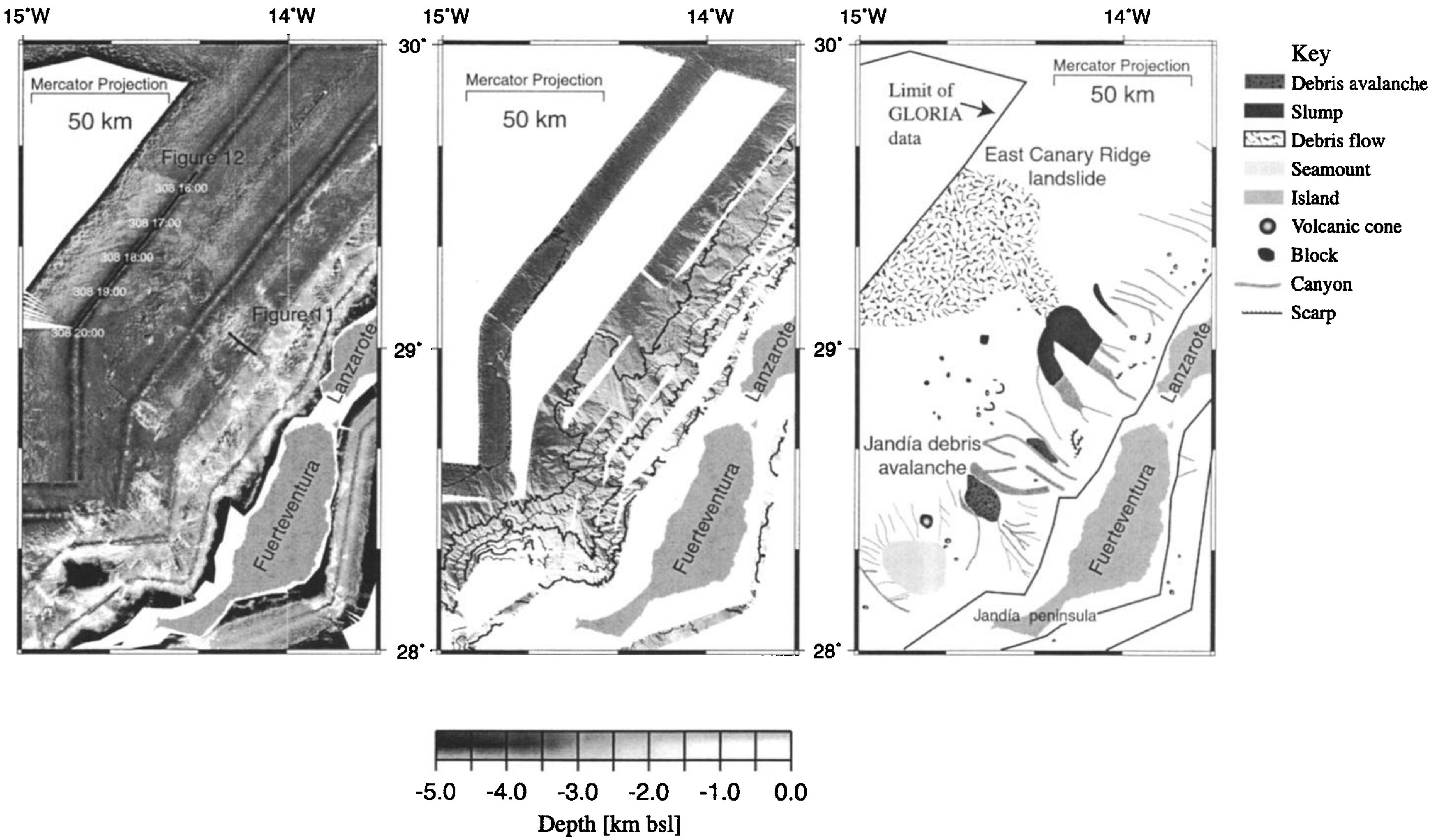

Figure 10. (left) GLORIA mosaic, (middle) bathymetric multibeam, and (right) interpretation map around the East Canary Ridge. Dark tones in the GLORIA mosaic are areas of low backscatter. The bathymetric map is shaded by artificial illumination from the north-northeast. The contour interval is 0.5 km, and the 1 km isolines are plotted in bold. See Figure 3 for location.

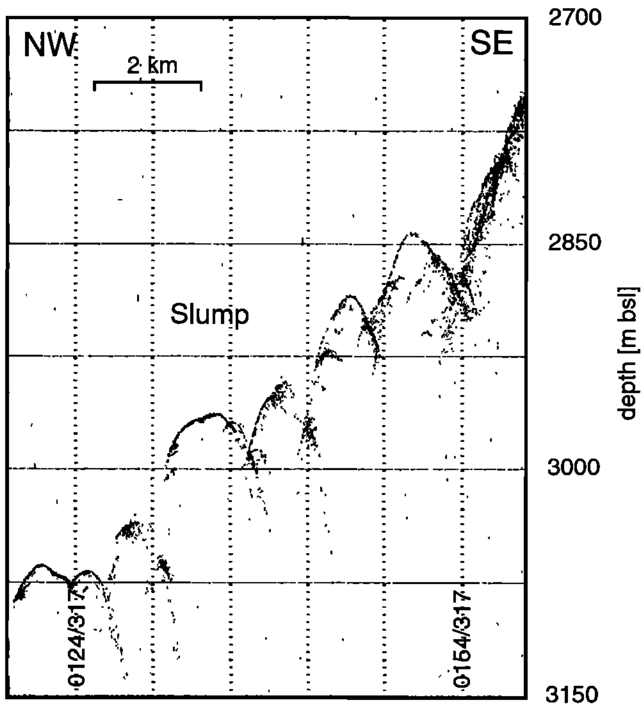

Figure 11. A 3.5-kHz profile across the rotational slump off the strait between Lanzarote and Fuerteventura. The profile shows a characteristic step pattern of a series of rotational slip planes. See Figure 10 for location.

been important in verifying the landslide/debris avalanche interpretation. However, hummocky features on the seafloor as well as scarps on an island can be, and also have been, interpreted in other ways. Seismic studies have, in some cases, helped to map such deposits [e.g., *Urgeles et al.*, 1997], but the impedance of the deposits is generally too high to make a detailed seismic study very enlightening.

In the Canary Islands, two other criteria have been used to identify and quantify debris avalanche events. One is the occurrence of major debris avalanche deposits on land, by far the most striking being the Pliocene Roque Nublo debris avalanche deposit [*García Cacho et al.*, 1994; *Mehl and Schmincke*, 1999], while seismic reflection studies in combination with drilling the clastic apron of Gran Canaria have allowed tracing and lithological study of at least three, possibly as many as six, major collapse events on the island [*Funck and Schmincke*, 1998; *Schmincke and Sumita*, 1998]. Volume, ages, and the methods used for identifying the landslides around the Canary Islands are listed in Table 1.

6.1. Submarine Morphology: Are Hummocks Volcanic Cones or Exotic Blocks?

The size of submarine hummocks in the areas affected by debris avalanches on the submarine flanks of the Canary Islands varies considerably. Some blocks, ~10%, have diameters up to 2.5 km and are more than 300 m high. The remaining 90% of the blocks are much smaller with diameters of 50–1000 m and have heights of 10–150 m. Almost all of the larger blocks are found close to the coast (<10 km) at water depths of <1200 m. These areas are characterized by a few (usually <10) large single blocks, while the deeper parts are characterized by hundreds of smaller hummocks. It is difficult, however, to distinguish between volcanic cones and exotic blocks based on bathymetric data alone.

One of the larger hummocks (basal dimensions of 2.5 x 1.7 km, height of 300 m) located off Güimar valley (28°13.5'N, 16°18.1'W) sampled during Meteor cruise M43-1 turned out to be a submarine scoria/lapilli cone rather than a landslide block [*Schmincke et al.*, 2000]. No samples are available for other hummocks, but some of the large single hummocks close to the coast are probably also volcanic structures, indicating that the landslide area has been modified by postfailure volcanism. Postfailure volcanism on the islands is common. Examples are the rapidly filled Horgazales basin on Gran Canaria [*Schmincke*, 1968] and most of the large Pliocene/Pleistocene landslide scars on Tenerife [*Ancochea et al.*, 1990, 1999]. The majority of hummocks, however, are interpreted as exotic blocks transported by debris avalanches. Such high numbers of small and large hummocks on the lower slopes are not found elsewhere on the submarine flanks of the Canary Islands. The dimensions of the blocks fit well with those reported from other debris avalanche deposits at the submarine flanks of volcanic islands, e.g., the El Golfo debris avalanche west of El Hierro [*Masson*, 1996; *Urgeles et al.*, 1997], debris avalanche deposits west of Réunion Island [*Labazuy*, 1996], and the debris avalanches along the Hawaiian Ridge [*Lipman et al.*, 1988; *Moore et al.*, 1989, 1994]. Nevertheless, it cannot be excluded that some hummocks on the lower slope are volcanic constructional features.

6.2. Distribution and Timing of Landslides

So far, 12 giant landslides with a length >20 km were identified on the submarine flanks of the Canary Islands by bathymetric and side-scan data (Figure 4). These landslides must be relatively young because otherwise they would have been buried under sediments due to high sedimentation rates around the Canary Archipelago. Sedimentation rates are ~70 m/Myr in the Pleistocene as shown by drilling around Gran Canaria [*Schmincke et al.*, 1995]. Hence blocks <140 m high are not detectable on sonographs or bathymetric maps after 2 Myr. The majority of the blocks of the debris avalanches identified on the flanks of the Canary Islands (e.g., Güimar debris avalanche, El Julán debris avalanche, and Las Playas debris avalanche) are <140 m high.

The majority of giant landslides around the Canary Archipelago were found at the volcanically most active and youngest islands of El Hierro, La Palma, and Tenerife, but large mass-wasting events were also identified morphologically for the first time on the flanks of the older (15–20 Ma) but still active eastern islands. Thus large landslides on the Canaries not only occur during the shield-building phase but also during later volcanic phases. The long-term volcanic activity of the islands of the Canary Archipelago is balanced by a corresponding long history of destruction.

The occurrence of giant landslides during phases of major volcanic activity is especially well documented at the islands with a long volcanic history. On Gran Canaria, several large landslides were identified during the Miocene volcanic phase [*Funck and Schmincke*, 1998]. A large stratovolcano, built during the second major volcanic phase in the Pliocene, collapsed at circa 3.5 Ma, forming the Roque Nublo debris avalanche [*García Cacho et al.*, 1994; *Mehl and Schmincke*, 1999]. The Quaternary volcanic/magmatic activity was not voluminous enough to produce large landslides. On Tenerife, several unconformities in the western Teno shield complex are interpreted as due to major flank collapses (J.M. Navarro and T. Walter, unpublished data,

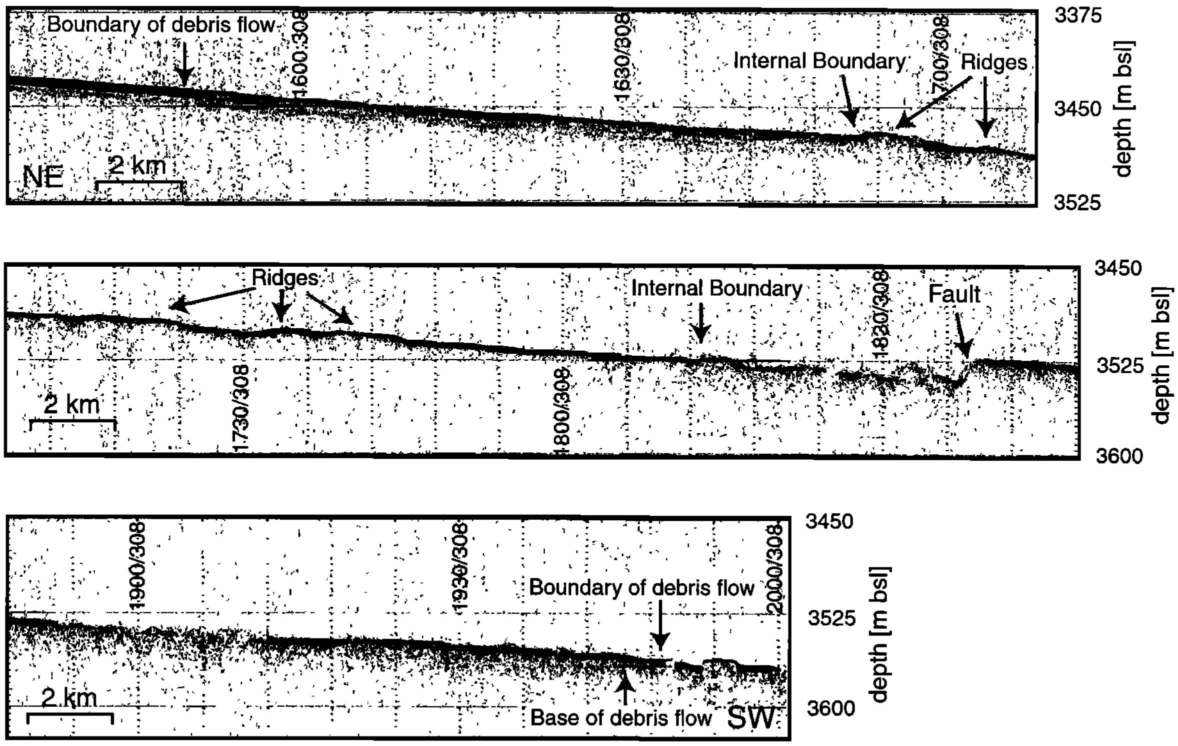

Figure 12. A 3.5 kHz profile across the debris flow deposits off the strait between Lanzarote and Fuerteventura. The northern boundary is characterized by a change from a distinct to a prolonged echo, while the debris flow deposits onlap the sediments at the southern boundary. See Figure 10 for location.

2000). Moreover, the high accumulation rates of volcanic turbidites in the Madeira Abyssal Plain since 7 Ma [*Weaver et al.*, 1998] indicate major mass-wasting events during growth of the Teno complex. Large landslides occurred during the later volcanic phases. Several collapse events occurred during the construction of the large Cañadas volcano in the center of the islands, e.g., Icod and the Las Bandas del Sur debris avalanche, and large landslides originated at the Cordillera Dorsal (e.g., Orotava and Güimar debris avalanche).

Stillman [1999] postulates giant Miocene landslides along the East Canary Ridge to explain the rapid denudation of early to mid-Miocene peaks as high as 3500 m in less than 2 Myr. As shown by this study, giant mass wasting still plays an important role during the Quaternary evolution of the East Canary Ridge.

6.3. Landslide Frequency and Landslide Hazards

Twelve giant landslides deposited on the submarine flanks of the Canary Islands during the last 1.5 to 2 Myr result in an average of one giant landslide every 125–170 kyr in the Pleistocene. Additional mass-wasting events occurred in this period, but they are covered by younger landslides or sediments preventing the detection on bathymetric and side-scan data. Numerous indications for further flank collapses, such as listric slip planes covered by a breccia, were found on Tenerife through observations in the tunnels penetrating the island for water extraction (J.M. Navarro and T. Walter, personal communication, 2000) as well as other geological studies [*Cantagrel et al.*, 1999]. Additional landslides are reported on La Palma [*Navarro and Coello*, 1993; *Ancochea et al.*, 1994; *Carracedo et al.*, 1999] and El Hierro [*Guillou et al.*, 1996; *Day et al.*, 1997] through studies on land. The occurrence of one landslide every 125–170 kyr in the Pleistocene is therefore a minimum value. *Urgeles et al.* [1997] estimate that nine major landslides occurred in the last 1.2 Myr, resulting in an average of one landslide every 133 kyr. Though this value is in good agreement with the value estimated in this paper, they take into account two additional landslides on El Hierro and La Palma not used in this study because no deposits of these landslides have as yet been identified on the submarine flanks, but they did not have any information about mass wasting on the East Canary Ridge. *Masson* [1996] suggests that volcaniclastic turbidites deposited at the Madeira Abyssal Plain (MAP) are linked to volcano flank landslides in the Canary Archipelago. Especially the b and g MAP turbidites correlate almost exactly with the El Golfo debris avalanche on El Hierro and the Icod landslide on Tenerife in terms of age and geochemical signature. Seven volcaniclastic turbidites have been deposited in the Madeira Abyssal Plain since 750 ka [*Weaver et al.*, 1992], suggesting a frequency of one giant landslide every 100 kyr. A similarly high landslide frequency occurred at least since 7 Ma because drilling at the Madeira Abyssal Plain revealed an increased frequency and accumulation rate of volcanic turbidites in this period [*Lebreiro et al.*, 1998; *Weaver et al.*, 1998]. It remains unclear why only minor amounts of volcanic turbidites were found in the Madeira Abyssal Plain prior to 7 Ma. Possibly, turbidites shed from the older eastern islands were trapped in a local basin that had filled by 7 Ma or the birth of Tenerife at this time may have breached the western margin of this local basin [*Lebreiro et al.*, 1998]. Giant landslides, however, occurred during the Miocene shield building-phase of Gran Canaria [*Funck and Schmincke*, 1998; *Schmincke and Segschneider*, 1998] and Fuerteventura [*Stillman*, 1999], though it is not possible to estimate the landslide frequency for this period.

The geological hazard of large flank collapses cannot be estimated well from the data available. The value of one giant landslide every 125–170 kyr in the Pleistocene around the Canary Islands is a minimum value. Four giant landslides occurred since 200 ka on the flanks of El Hierro and Tenerife resulting in one landslide every 50 kyr during this period. Smaller but more frequent events most likely occurred as well.

Rift zones play a key role in the distribution of geological hazards in the Canary Islands, and failure planes of gravitational landslides are located preferentially along these volcanic lineaments [*Carracedo*, 1996]. Hence the islands of Tenerife, La Palma, and El Hierro with voluminous young volcanic activity and distinct rift zones are the most probable places for future landslide initiation, but sliding may occur on the other islands as well.

Two areas should be treated with special care. Broadly curving faults opened during the 1949 eruption in La Palma [*Bonelli Rubio*, 1950], probably as a result of the stresses working to collapse the west flank of the southern rift with slope angles exceeding 15° [*Carracedo*, 1996]. The second area is the San Andres fault system on El Hierro. It is unclear whether the San Andres fault system is a natural hazard or not. *Day et al.* [1997] point out that the San Andres fault system is an old, inactive structure which was not reactivated during subsequent collapses elsewhere on El Hierro, and thus the probability of a catastrophic lateral collapse is very much reduced in the near future. *Carracedo* [1996], in contrast, interprets the concentration of recent eruptive vents on the northeast and south rifts of El Hierro as an indication that this part of the island seems to be the most active recently and therefore a location for a potential flank collapse. Submarine volcanic cones found by us east of El Hierro and on the submarine continuation of the south rift (Figure 5) support this interpretation.

The main hazards associated with flank collapses on the Canary Islands are the landslide itself, the tsunamis triggered by slides, and large lateral blasts due to explosion of hydrothermal or magmatic systems. A giant blast deposit covering much of central and western Tenerife is associated with a collapse of the Cañadas volcano circa 180 ka [*Schmincke et al.*, 1999]. Not much is known about tsunami deposits in the Canary Islands region. An exotic sandstone on top of a thick debris flow deposit was drilled during ODP Leg 157 (Site 956) southwest of Gran Canaria [*Schmincke et al.*, 1995]. *Schmincke and Segschneider* [1998] interpret the huge basal debris flow as deposits related to the collapse of the Miocene shield of southwestern Gran Canaria and assume that this collapse caused a major tsunami that washed up beach sands on La Gomera, ~115 km west of Gran Canaria. No young unequivocal tsunami deposits are reported from the Canary Islands as yet. The Alika debris avalanches on the west flank of the Island of Hawaii probably triggered the tsunami that deposited gravel perhaps as high as 326 m asl on the island of Lanai [*Moore and Moore*, 1984; *Lipman et al.*, 1988], but this colossal height is now strongly disputed [*Keating*, 1997; *Felton et al.*, 2000]. Though most debris avalanches on the flanks of the Canary Islands have lower volumes than the Alika debris avalanches, they are certainly large enough to generate tsunamis. Tsunamis are therefore a serious hazard for the densely populated coastal areas of the Canary Islands.

6.4. Triggering Mechanisms

The potential causes for instability and flank failure are numerous but not well understood. Mechanisms include, among others, oversteepening of the flanks due to magma intrusion or rapid accumulation, displacement due to dike intrusion, surface loading, volcanic and tectonic seismicity, and vertical tectonics. The single, linking, contributory factor, however, is gravity [*McGuire*, 1996].

The islands of Tenerife, La Palma, and El Hierro show distinct rift-type volcanic features. The locations of the depressions at the head of the landslides are located perpendicularly to the rifts, and hence we favor a destabilization of the flanks due to dike-induced rifting. Dike-induced rifting is one of the major causes of edifice destabilization and failure [*McGuire*, 1996]; structural collapse is more common at edifices characterized by the existence of parallel dike swarms [*Siebert*, 1984]. *Carracedo* [1994] points out that extensional stress in rift zones tends to build up until reaching the rupture threshold.

In some islands such as La Palma, Tenerife, La Gomera, Gran Canaria, and Fuerteventura prominent high level dominantly phonolitic domes are exposed. Forceful intrusion of such highly viscous magma must be very effective in bringing about a major dilatation, the best documented case so far being the domes in the Roque Nublo stratocone and the abundant intrusions of the Fataga cone sheet swarm [*Schirnick et al.*, 1999] that may have triggered the Miocene phonolitic debris avalanches on Gran Canaria.

The slides along the East Canary Ridge may be triggered by volcanic/magmatic activity as well. The areas on the island adjacent to the slides show voluminous volcanism in the Pleistocene [*Coello et al.*, 1992], and we identified several volcanic cones on the submarine flanks of the East Canary Ridge on the sonograph and bathymetric map. Surface loading due to volcanic activity and/or rising sea level can be another reason for the destabilization of the flanks. The majority of turbidites in the Madeira Abyssal Plain were deposited at times of falling and rising sea levels through the last 750 kyr, suggesting that sea level changes play an important role for triggering submarine landslides [*Weaver et al.*, 1998].

The East Canary Ridge landslide, consisting of two slumps and a debris flow, shows a sequence of interdependent trigger events. The debris flow of the East Canary Ridge landslide originated at ~3300 m bsl on a slope of ~1°. The position of the debris flow suggests that it was triggered by the rotational slump, which originated farther upslope. *Roberts and Cramp* [1996] postulate, on the basis of a geotechnical study, a similar progressive style trigger mechanism for the Canary debris flow off El Hierro, perhaps the most likely mechanism by which disintegrative failures occur on the submarine slopes of the Canary Islands.

6.5. Comparison of Canarian With Hawaiian Landslides

At least 68 major landslides more than 20 km long were found along a 2200-km stretch of the Hawaiian Ridge from 200 km northwest of Midway to the Island of Hawaii. Landslides cover about one half of the flanks of the ridge and average one every 350 kyr [*Moore et al.*, 1994]. Landslides appear to occur less frequently on the Hawaiian Ridge compared to the Canary Archipelago, though the value for the Hawaiian Ridge has been determined for a much longer period of time. Several landslides are thought to be covered by continued growth of the Hawaiian Ridge, but this is also valid for the Canary Islands (e.g., large parts of the submarine flank of Gran Canaria are covered by the younger volcanic flank of Tenerife). Seven giant landslides were found on the submarine flanks of the Island of Hawaii, the youngest island of the Hawaiian Archipelago [*Moore et al.*, 1989]. The age of the oldest of these landslides, the Polulu debris avalanche, is circa 400 ka [*Moore et al.*, 1989; *Normark et al.*, 1993], and therefore one giant landslide occurred approximately every 60 kyr from then on. A similar value can be obtained for El Hierro where three landslides occurred since 200 ka, but at least two additional landslides (Icod debris avalanche on Tenerife and the East Canary Ridge landslide) occurred during this period as well.

The characteristics of the Miocene flank collapses of Gran Canaria explain why only a small number of landslides were identified by means of bathymetric and side-scan data on the flanks of the Canary Archipelago compared to the Hawaiian Ridge. The Miocene landslides around Gran Canaria are long buried under a thick sediment cover due to high sedimentation rates (in general >50 m/Myr) in this area [*Schmincke et al.*, 1995; *Funck and Schmincke*, 1998] and by the growth of Tenerife to the west. In contrast, debris avalanches older than 25 Ma were identified on sonographs around Midway Islands some 2400 km west-northwest of the Island of Hawaii, where sedimentation rates are very much lower (~2.5 m/Myr) than around the Canaries [*Moore et al.*, 1994].

Surprisingly, landslide frequency on the Hawaiian Archipelago may be less than that on the Canary Archipelago. Magma intrusion and eruption rates are much higher for the Hawaiian compared to the Canary Islands, but this is not reflected by a higher landslide frequency. The volume of single landslide deposits, however, is higher for the Hawaiian Islands. The largest landslide of the Hawaiian Ridge, the Nuuanu debris avalanche, covers 23,000 km^2 on the northeast flank of Oahu and has an estimated volume of 5000 km^3. The largest landslide field of the Canary Archipelago, in contrast, the amalgamated Icod/Orotava debris avalanche, covers ~5000 km^2 on the northwest flank of Tenerife with an estimated volume of 1000 km^3 [*Watts and Masson*, 1995].

Many more volcanic phases on individual islands, mostly accompanied by flank failure, are the main reason for the higher landslide frequency at the Canary Islands. This results in a higher landslide frequency but a smaller average volume of the landslides due to the smaller magma production rates during the later volcanic phases. In addition, the slopes of the Canary Islands are steeper than the slopes of the Hawaiian Ridge, probably due to the large amount of highly differentiated magmas on the Canary Islands. The alkalic magmas in the Canary Archipelago are also richer in volatiles compared to the tholeiitic magmas of the Hawaiian Archipelago, resulting in more frequent submarine and subaerial explosive eruptions. Hence abundant pyroclastic deposits are found on the subaerial and submarine flanks of the Canary Islands [*Schmincke et al.*, 2000] being less stable than Hawaiian island flanks dominantly built of massive lavas.

One of the main differences between the Hawaiian and the Canary Archipelagos is the longer-lasting volcanic activity of single islands for the latter. Fuerteventura, Lanzarote, and Gran Canaria have been active for >15 Myr, while volcanic activity on single Hawaiian Islands did not last longer than ~4 Myr. The largest landslides on the Hawaiian Ridge apparently occur late in the period of active shield growth when the volcanoes are close to their maximum size and are young and unstable and when seismic activity is high. Hence the ages of volcanoes along the ridge are mirrored by the ages of their associated landslides, and young landslides are only found at the youngest and active end of the ridge [*Moore et al.*, 1994]. In contrast, young landslides around the Canary Islands occur during all phases of major magmatic activity and have been identified on the flanks of even the oldest islands of the archipelago (Figure 13).

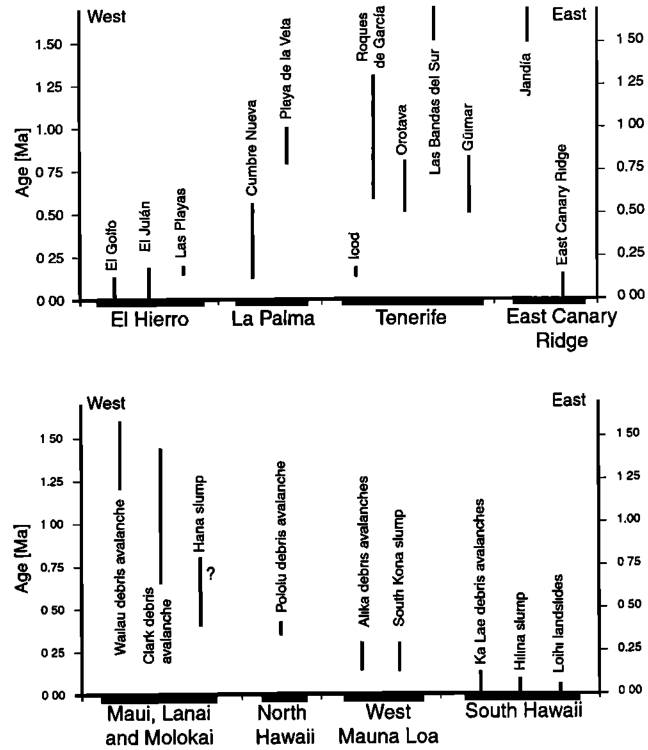

Figure 13. Comparison of the distribution and timing of landslides at the (top) Canary and (bottom) Hawaiian Archipelagos. The age of the shield stages is increasing from west to east for the Canary Islands and from east to west for the Hawaiian Islands. While the ages of the shields of the Hawaiian Islands are mirrored by the ages of their associated landslides, giant mass wasting is an important process during the entire evolution of the islands of the Canary Archipelago. Ages of the Hawaiian landslides are taken from *Moore et al.* [1989] and *Normark et al.* [1993].

7. Conclusions

Bathymetric and GLORIA side-scan data collected around the Canary Islands have revealed the widespread occurrence of submarine landslides during the evolution of an island group in the Atlantic Ocean, such as the Canary Islands.

1. Twelve giant submarine landslides >20 km long were found on the flanks of the Canary Islands using side-scan and bathymetric data. These landslides must be relatively young (<2 Ma), as they would long have been buried under sediments due to high sedimentation rates (in general >50 m/Myr) around the Canary Islands.

2. Giant landslides have been identified on the flanks of the older (15-20 Ma) but still active islands of the East Canary Ridge for the first time. The occurrence of young giant landslides on the flanks of the older islands of the archipelago is one of the main differences to the Hawaiian Islands, where giant landslides mainly occur late in the period of active shield growth and young landslides are only found at the youngest and active end of the ridge.

3. Land studies, borehole data, and seismic studies have allowed us to trace older major collapse events on the Canary Islands. All periods of major magmatic activity are accompanied by large-scale mass wasting. The long-lasting volcanic activity of the islands of the Canary Archipelago is balanced by a corresponding long history of destruction.

4. An average of at least one giant landslide every 125-170 kyr in the Pleistocene was estimated for the Canary Islands. This value equals or might exceed that for the Hawaiian Ridge, even though magmatic intrusion and eruption rates are much higher for the Hawaiian Islands. The causes for the higher frequency of landslides on the Canaries include multiple volcanic phases, each accompanied by large-scale mass wasting, the steeper slopes of the Canary Islands, and large amounts of pyroclastic deposits even at water depths >1000 m at the Canary Islands resulting in less stable flanks. The volume of single landslide deposits, however, is smaller than for the Hawaiian Islands.

5. The main reason for the destabilization of the flanks is thought to be dike-induced rifting. Another reason for destabilization is surface loading due to volcanic activity and/or rising sea levels.

6. The majority of the hummocks on the submarine flanks are exotic blocks, but some hummocks, especially close to the source areas of the landslides, are volcanic structures, evidence for postfailure volcanism.

7. Landslides on the flanks of the Canary Islands are a potential hazard due to the deposition of the landslide itself, the tsunamis they can trigger, and large lateral blasts associated with the explosion of magmatic and hydrothermal systems. The islands of La Palma, El Hierro, and Tenerife with ongoing voluminous volcanic activity and distinct rift zones are the most probable locations for future landslide initiation, but landslides may occur on the other islands as well.

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References

Ancochea, E, J M. Fúster, E Ibarrola, A. Cendrero, J. Coello, F. Hernán, J M. Cantagrel, and C Jamond, Volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K-Ar data, *J. Volcanol. Geotherm Res*, *44*, 231-249, 1990.

Ancochea, E., F. Hernán, A. Cendrero, J.M. Cantagrel, J.M. Fúster, E. Ibarrola, and J Coello, Constructive and destructive episodes in the building of a young oceanic island, La Palma, Canary Islands, and genesis of the caldera de Taburiente, *J Volcanol Geotherm. Res.*, *60*, 243-262, 1994.

Ancochea, E., M.J. Huertas, J M. Cantagrel, J Coello, J.M. Fúster, N Arnaud, and E Ibarrola, Evolution of the Cañadas edifice and its implications for the origin of the Cañadas Caldera (Tenerife, Canary Islands), *J. Volcanol. Geotherm. Res.*, *88*, 177-199, 1999.

Anguita, F., and F. Hernán, A propagating fracture model versus hot spot origin for the Canary Islands, *Earth Planet. Sci. Lett.*, *27*, 11-19, 1975.

Araña, V, and R. Ortiz, The Canary Islands: Tectonics, magmatism and geodynamic framework, in *Magmatism in Extensional Structural Settings*, edited by A B. Kampunzu and R.T. Lubala, pp. 209-249, Springer-Verlag, New York, 1991.

Banda, E., J.J. Dañobeitia, E. Surinach, and J. Ansorge, Features of crustal structure under the Canary Islands, *Earth Planet Sci. Lett.*, *55*, 11-24, 1981.

Bogaard, P. van den, and H.-U. Schmincke, Chronostratigraphy of Gran Canaria, *Proc. Ocean Drill. Program Sci. Results*, *157*, 127-140, 1998.

Bonelli Rubio, J.M., *Contribución al Estudio de la Erupción del Nambroque o San Julan (Isla de La Palma)*, Inst. Geogr. Castral, Madrid, Spain, 1950.

Bosshard, E., and D.J. MacFarlane, Crustal structure of the western Canary Islands from seismic refraction and gravity data, *J. Geophys. Res.*, *75*, 4901-4918, 1970.

Cantagrel, J.M., A. Cendrero, J.M. Fúster, E. Ibarrola, and C. Jamond, K-Ar chronology of the volcanic eruptions in the Canarian Archipelago: island of La Gomera, *Bull. Volcanol*, *47*, 597-609, 1984.

Cantagrel, J.M., N.O. Arnaud, E. Ancochea, J.M. Fúster, and M.J. Huertas, Repeated debris avalanches on Tenerife and genesis of Las Cañadas caldera wall (Canary Islands), *Geology*, *27*, 739-742, 1999.

Carracedo, J.C., The Canary Islands: An example of structural control on the growth of large oceanic-island volcanoes, *J. Volcanol. Geotherm. Res.*, *60*, 225-241, 1994.

Carracedo, J.C., A simple model for the genesis of large gravitational landslide hazards in the Canary Islands, in *Volcano Instability on the Earth and Other Planets*, edited by W.J McGuire, A.P. Jones, and J. Neuberg, *Geol. Soc. Spec. Publ.*, *110*, 125-135, 1996.

Carracedo, J.C., S J. Day, H. Guillou, and P. Gravestock, Later stages of volcanic evolution of La Palma, Canary islands: Rift evolution, giant landslides, and the genesis of the Caldera de Taburiente, *Geol. Soc. Am. Bull*, *111*, 755-768, 1999.

Coello, J., J.-M. Cantagrel, F Hernán, J.-M. Fúster, E. Ibarrola, E. Ancochea, C. Casquet, C Jamond, J.-R. Díaz de Téran, and A. Cendrero, Evolution of the eastern volcanic ridge of the Canary Islands based on new K-Ar data, *J. Volcanol. Geotherm. Res.*, *53*, 251-274, 1992.

Crandell, D.R., C.D Miller, H.X. Glicken, R.L Christiansen, and C.G. Newhall, Catastrophic debris avalanche from ancestral Mount Shasta volcano, California, *Geology*, *12*, 143-146, 1984.

Day, S.J., J.C. Carracedo, and H. Guillou, Age and geometry of an aborted rift flank collapse: the San Andres fault system, El Hierro, Canary Islands, *Geol. Mag.*, *134*, 523-537, 1997.

Embley, R.W., Anatomy of some Atlantic margin sediment slides and some comments on ages and mechanisms, in *Marine Slides and Other Mass Movements*, edited by S. Saxov and J.K. Nieuwenhuis, pp. 189-213, Plenum, New York, 1982.

Felton, E.A., K.A.W. Crook, and B.H. Keating, The Hulopoe gravel, Lanai, Hawaii: New sedimentological data and their bearing on the "giant wave" (mega-tsunami) emplacement hypothesis, *Pure Appl. Geophys.*, *157*, 1257-1284, 2000.

Funck, T., Structure of the volcanic apron north of Gran Canaria deduced from reflection seismic, bathymetric and borehole data, Ph.D. thesis, Christian-Albrechts-Univ. zu Kiel, Kiel, Germany, 1996.

Funck, T., and H.-U. Schmincke, Growth and destruction of Gran Canaria deduced from seismic reflection and bathymetric data, *J. Geophys Res*, *103*, 15,393-15,407, 1998.

García Cacho, L., J.L. Díez-Gil, and V Araña, A large volcanic debris avalanche in the Pliocene Roque Nublo Stratovolcano, Canary Islands, *J. Volcanol. Geotherm. Res.*, *63*, 217-229, 1994.

Guillou, H., J.C. Carracedo, F Pérez Torrado, and E. Rodríguez Badiola, K-Ar ages and magnetic stratigraphy of a hotspot-induced, fast grown oceanic island: El Hierro, Canary Islands, *J. Volcanol. Geotherm Res*, *73*, 141-155, 1996

Hausen, H., Some contributions to the geology of La Palma, *Commentat Phys Math.*, *35*, 1-140, 1969.

Hausen, H, Rockfalls, landslides, and creep in the Canaries, *Acta Geogr*, *23*, 1-43, 1971.

Hinz, K, H Dostmann, and F Fritsch, The continental margin off Morocco: Seismic sequences, structural elements and geological development, in *Geology of the Northwest African Continental Margin*, edited by U. von Rad, K. Hinz, M Sarnthein, and E. Seibold, pp. 34-60, Springer-Verlag, New York, 1982.

Hoernle, K.A., and H.-U Schmincke, The role of partial melting in the 15-Ma geochemical evolution of Gran Canaria: A blob model for the Canary hotspot, *J Petrol.*, *34*, 599-626, 1993.

Holcomb, R.T., and R.C. Searle, Large landslides from oceanic volcanoes, *Mar. Geotechnol.*, *10*, 19-32, 1991

Ibarrola, E, E Ancochea, J.M. Fúster, J.M. Canatagrel, J. Coello, N J. Snelling, and M.J. Huertas, Cronoestratigrafía del Macizo de Tigaiga: evolucíon de un sector del Edificio Cañadas (Tenerife, Islas Canarias), *Bol. R. Soc. Esp. Hist. Nat. Secc. Geol.*, *88*, 57-72, 1993

Jacobs, B., Reflexionsseismische Strukturen der Kanarischen Inselflanken. Ein Beitrag zur zeitlichen Entwicklung der Sedimentationsgeschichte des Kanarischen Beckens, Diplomarbeit, Christian-Albrechts-Univ. zu Kiel, Kiel, Germany, 1999.

Keating, B., Are the coastal gravels on Lanai tsunami deposits? (abstract), *Geol. Soc. Am. Abstr. Programs*, *29*(5), 22, 1997.

Kidd, R.B., R.W. Simm, and R.C. Searle, Sonar acoustic facies and sediment distribution on an area of the deep ocean floor, *Mar. Petr. Geol.*, *2*, 210-221, 1985.

Krastel, S., H.-U. Schmincke, and C.L. Jacobs, Formation of submarine canyons on the flanks of the Canary islands, *Geo Mar. Lett*, in press, 2000.

Labazuy, P., Recurrent landslides event on the submarine flank of Piton de la Fournaise volcano (Réunion Island), in *Volcano Instability on the Earth and Other Planets*, edited by W.J. McGuire, A.P. Jones, and J. Neuberg, *Geol. Soc. Spec. Publ*, *110*, 295-306, 1996.

Le Bas, T.P., M.L. Somers, J.M. Campbell, and R. Beale, Swath bathymetry with Gloria, *IEEE J. Oceanic Eng.*, *21*, 545-553, 1996.

Lebreiro, S.M., P.P.E. Weaver, and R.W. Howe, Sedimentation on the Madeira Abyssal Plain: Eocene-Pleistocene history of turbidite infill, *Proc. Ocean Drill. Program. Sci. Results*, *157*, 523-531, 1998.

Lee, H.J., W.C. Schwab, and J.S. Booth, Submarine landslides: an introduction, in *Submarine Landslides: Selected Studies in the U.S. Exclusive Economic Zone*, edited by W.C. Schwab, H.J. Lee, and D.C. Twichell, *U.S. Geol. Surv. Bull.*, *2002*, 1-13, 1993.

Lipman, P.W., W.R. Normark, J.G. Moore, J.B. Wilson, and C.E. Gutmacher, The giant Alika debris slide, Mauna Loa, Hawaii, *J. Geophys. Res.*, *93*, 4279-4299, 1988.

Lyell, C., *A Manual of Elementary Geology*, 4th ed., 512 pp., London, 1853.

Martí, J., M. Hurlimann, G.J. Ablay, and A. Gudmundsson, Vertical and lateral collapses on Tenerife (Canary Islands) and other volcanic ocean islands, *Geology*, *25*, 879-882, 1997.

Masson, D.G., Catastrophic collapse of the volcanic island of Hierro 15 ka ago and the history of landslides in the Canary Islands, *Geology*, *24*, 231-234, 1996.

Masson, D.G., R.B. Kidd, J.V. Gardner, Q.J. Huggett, and P.P.E. Weaver, Saharan continental rise: facies distribution and sediment slides, in *Geologic Evolution of Atlantic Continental Rises*, edited by C.W. Poag and P.C. de Graciansky, pp. 327-343, Van Nostrand Reinhold, New York, 1992.

Masson, D.G., Q.J. Huggett, and D. Brunsden, The surface texture of the Saharan debris flow and some speculations on submarine debris flow processes, *Sedimentology*, *40*, 583-598, 1993.

Masson, D.G., M. Canals, B. Alonso, R. Urgeles, and V. Hühnerbach, The Canary debris flow: Source area morphology and failure mechanisms, *Sedimentology*, *45*, 411-432, 1998.

McDougall, I., and H.-U. Schmincke, Geochronology of Gran Canaria, Canary Islands: Age of shield building volcanism and other magmatic phases, *Bull. Volcanol.*, *40*, 57-77, 1976.

McGuire, W.J., Volcano instability: a review of contemporary themes, in *Volcano Instability on the Earth and Other Planets*, edited by W.J. McGuire, A.P. Jones, and J. Neuberg, *Geol. Soc. Spec. Publ.*, *110*, 1-23, 1996.

Mehl, K.W., and H.-U. Schmincke, Structure and emplacement of the Pliocene Roque Nublo debris avalanche deposit, Gran Canaria, Spain, *J. Volcanol. Geotherm. Res.*, *94*, 105-134, 1999.

Moore, J.G., and G.W. Moore, Deposit from a giant wave on the island of Lanai, Hawaii, *Science*, *226*, 1312-1315, 1984.

Moore, J.G., D.A. Clague, R.T. Holcomb, P.W Lipman, W.R. Normark, and M.E. Torresan, Prodigious submarine landslides on the Hawaiian Ridge, *J. Geophys. Res.*, *94*, 17,465-17,484, 1989.

Moore, J.G., W.R. Normark, and R.T. Holcomb, Giant Hawaiian landslides, *Annu. Rev. Earth Planet. Sci.*, *22*, 119-144, 1994.

Navarro, J.M., and J. Coello, Depressions originated by landslide processes in Tenerife, paper presented at ESF Meeting on Canarian Volcanism, Eur. Space Found., La Palma, Canary Islands, Spain 1989.

Navarro, J.M., and J. Coello, Sucesión de episodios en la evolución geológica de La Palma, Mapa geológico de La Palma, Inst. Nac. para la Conserv. de la Nat., Madrid, 1993.

Normark, W.R., J.G. Moore, and M.E. Torresan, Giant volcano-related landslides and the development of the Hawaiian Islands, in *Submarine Landslides: Selected Studies in the U.S. Exclusive Economic Zone*, edited by W.C. Schwab, H.J. Lee, and D.C. Twichell, *U.S. Geol. Surv. Bull.*, *2002*, 197-204, 1993.

Ridley, W.I., The origin of some collapse structures in the Canary Islands, *Geol. Mag.*, *108*, 447-484, 1971.

Roberts, J.A., and A. Cramp, Sediment stability on the western flanks of the Canary Islands, *Mar. Geol.*, *134*, 13-30, 1996.

Schirnick, C., P. van den Bogaard, and H.-U. Schmincke, Cone sheet formation and intrusive growth of an oceanic island-The Miocene Tejada complex on Gran Canaria (Canary Islands), *Geology*, *27*, 207-210, 1999.

Schmincke, H.-U., Faulting versus erosion and the reconstruction of the mid-Miocene shield volcano of Gran Canaria, *Geol. Mitt.*, *8*, 23-50, 1968.

Schmincke, H.-U., Geology of the Canary Islands, in *Biogeography and Ecology in the Canary Islands*, edited by G. Kunkel, pp. 67-184, W. Junck, The Hague, 1976.

Schmincke, H.-U., Volcanic and chemical evolution of the Canary Islands, in *Geology of the Northwest African Continental Margin*, edited by U. von Rad, K. Hinz, M. Sarnthein, and E. Seibold, pp. 273-306, Springer-Verlag, New York, 1982.

Schmincke, H.-U., *Geological Field Guide of Gran Canaria*, 2nd ed., 179 pp., Pluto, Witten, Germany, 1987.

Schmincke, H.-U., Zeitliche, strukturelle und vulkanische Entwicklung der Kanarischen Inseln, der Selvagens Inseln und des Madeira-Archipels, in *Die Reptilien der Kanarischen Inseln, der Selvagens-Inseln und des Madeira-Archipels*, edited by W. Bischoff, pp. 27-69, Aula-Verlag, Wiesbaden, Germany, 1998.

Schmincke, H.-U., and R. Rihm, Ozeanvulkan 1993, Cruise No. 24, 15 April-9 May 1993, Meteor-Berichte, *Rep. 94-2*, 88 pp., Univ. Hamburg, Hamburg, Germany, 1994.

Schmincke, H.-U., and B. Segschneider, Shallow submarine to emergent basaltic shield volcanism of Gran Canaria: Evidence from drilling into the volcanic apron, *Proc. Ocean Drill. Program Sci. Results*, *157*, 1998.

Schmincke, H.-U., and M. Sumita, Volcanic evolution of Gran Canaria reconstructed from apron sediments: Synthesis of VICAP project drilling, *Proc. Ocean Drill. Program Sci. Results*, *157*, 443-469, 1998.

Schmincke, H.-U., P.P.E. Weaver, J. Firth, and Shipboard Scientific Party, *Proceedings of the Ocean Drilling Program, Init. Reports*, vol. 157, 843 pp., Ocean Drill. Program, College Station, Tex., 1995.

Schmincke, H.-U., K. Hoernle, T.H. Hansteen, A. Klügel, and P. van den Bogaard, Fragments of Jurrasic MORB-type ocean crust on Gran Canaria, Lanzarote and La Palma (Canary Islands), *Earth Planet. Sci. Lett.*, *163*, 343-360, 1998.

Schmincke, H.-U., J.M. Navarro, and M. Sumita, A giant blast associated with flank collapse of the Cañadas volcano (Tenerife, Canary Islands) (abstract), *J. of Conf. Abstr.*, 753, 1999.

Schmincke, H.-U., S. Krastel, T. Hansteen, and M. Sumita, Preliminary results of METEOR-cruise M43-1, DECOS, in *DECOS/OMEX II, Cruise No. 43, 25 November 1998 - 14 January 1999. Meteor-Berichte, Rep. 00-2*, edited by H.-U. Schmincke and G. Graf, pp. 16-48, Univ. Hamburg, Hamburg, Germany, 2000

Siebert, L., Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions, *J. Volcanol. Geotherm. Res.*, *22*, 163-197, 1984.

Smith, M.S., and J.B. Shepherd, Tsunami waves generated by volcanic landslides: an assessment of the hazard associated with Kick 'em Jenny, in *Volcano Instability on the Earth and Other Planets*, edited by W.J. McGuire, A.P. Jones, and J. Neuberg, *Geol. Soc. Spec. Publ.*, *110*, 115-1230, 1996.

Somers, M.L., R.M. Carson, J.A. Revie, R.H. Edge, B.J. Barrow, and A.G. Andrews, GLORIA II-An improved long-range side-scan sonar, in *Oceanology International 1978, Technical Session J.*, pp. 16-24, B.P.S. Publ., London, 1978.

Stets, J., and P. Wurster, Atlas and Atlantic-Structural relations, in *Geology of the Northwest African Continental Margin*, edited by U. von Rad, K. Hinz, M. Sarnthein, and E. Seibold, pp. 69-85, Springer-Verlag, New York, 1982.

Stillman, C.J., Giant Miocene landslides and the evolution of Fuerteventura, Canary Islands, *J. Volcanol. Geotherm. Res.*, *94*, 89-104, 1999.

Sumita, M., H.-U. Schmincke, and S. Krastel, Recognizing major island flank collapses events in deep-sea sediments by widespread debrites and tsunami-related deposits: evidence in the volcanic aprons of Tenerife and Gran Canaria (ODP Leg 157), paper presented at IAVCEI General Assembly, Bali, Indonesia, July 18-22, 2000.

Teide Group, Morphometric interpretation of the northwest and southeast slopes of Tenerife, Canary Islands, *J. Geophys. Res.*, *102*, 20,325-20,342, 1997.

Theilen, F., M. Riedel, and Shipboard Scientific Party, Fahrtbericht FS Poseidon, Reise 236/97, Las Palmas-Viana do Castelo, *Rep. 3.-18.12.97*, Christian-Albrechts-Univ. zu Kiel, Kiel, Germany, 1997.

Urgeles, R., M. Canals, J. Baraza, B. Alonso, and D. Masson, The most recent megalandslides of the Canary Islands: El Golfo debris avalanche and Canary debris flow, west El Hierro Island, *J. Geophys. Res.*, *102*, 20,305-20,323, 1997.

Urgeles, R., D.G. Masson, M. Canals, A.B. Watts, and T. Le Bas, Recurrent large-scale landsliding on the west flank of La Palma, Canary Islands, *J. Geophys. Res.*, *104*, 25,331-25,348, 1999.

Varnes, D.J., Slope movement types and processes, in *Landslides, Analysis and Control*, edited by R.L. Schuster and R.J. Krizek, pp. 11-28, Natl. Acad. of Sci. U.S.A., Washington, D.C., 1978.

Voight, B., H. Glicken, R.J. Janda, and P.M. Douglass, Catastrophic rockslide avalanche of May 18, in *The 1980 Eruptions of Mount St. Helens, Washington*, edited by D.R. Lipman and D.R. Mullineaux, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 347-400, 1981.

von Buch, L., *Physikalische Beschreibung der Canarischen Inseln*, 201 pp., Koenigl. Akad. Wiss., Berlin, 1825.

von Humboldt, A., *Voyages aux Régions Équinoxiales du Nouveau Continent, 1799-1804*, Paris, 1814.

Watts, A.B., and D.G. Masson, A giant landslide on the north flank of Tenerife, Canary Islands, *J. Geophys. Res.*, *100*, 24,487-24,498, 1995.

Watts, A.B., and D.G. Masson, Reply to comment by J. Martí on "A giant landslide on the north flank of Tenerife, Canary Islands", *J. Geophys. Res.*, *103*, 9949-9952, 1998.

Weaver, P.P.E., R.G. Rothwell, J. Ebbing, D. Gunn, and P.M. Hunter, Correlation, frequency of emplacement and source directions of megaturbidites on the Madeira Abyssal Plain, *Mar. Geol.*, *109*, 1-20, 1992.

Weaver, P.P.E., I. Jarvis, S.M. Lebreiro, B. Alibés, J. Baraza, R. Howe, and R.G. Rothwell, Neogene turbidite sequence on the Madeira Abyssal Plain: Basin filling and diagenesis in the deep ocean, *Proc. Ocean Drill. Program Sci. Results*, *157*, 619-634, 1998.

Wessel, P., and W.H.F. Smith, Free software helps map and display data, *Eos Trans. AGU*, *72*, 441, 445-446, 1991.

Wilson, J.T., Mantle plumes and plate motions, *Tectonophysics*, *19*, 149-164, 1973.

Wolfe, C.J., M.K. McNutt, and R.S. Detrick, The Marquesas archipelagic apron: Seismic stratigraphy and implications for volcano growth, mass wasting, and crustal underplating, *J. Geophys. Res.*, *99*, 13,591-13,608, 1994.

B. Alibés, National Geographic, Pérez Galdós 36, E-08012 Barcelona, Spain. (barbara-alibes@rba.es)

C.L. Jacobs and T.P. Le Bas, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, England, United Kingdom. (clj@soc.soton.ac.uk, tlb@soc.soton.ac.uk)

S. Krastel, Universität Bremen, Fachbereich Geowissenschaften, Postfach 330440, D-28334 Bremen, Germany. (skrastel@uni-bremen.de)

R. Rihm and H.-U. Schmincke, GEOMAR, Abteilung Vulkanologie und Petrologie, Wischhofstr. 1-3, D-24148 Kiel, Germany. (rolandrihm@aol.com, hschmincke@geomar.de)

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